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HYBRIDPRINT: A DUAL-TASK BIOMETRIC FRAMEWORK FOR GENDER PREDICTION AND ALTERATION DETECTION USING RIDGE DENSITY AND CNN FEATURE FUSION: A SYSTEMATIC REVIEW

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ABSTRACT

Fingerprint-based biometric systems are widely used for personal identification due to the uniqueness and reliability of fingerprint patterns. However, these systems face challenges from altered fingerprints, where individuals intentionally modify ridge structures to evade recognition. Over the years, various techniques have been developed, ranging from traditional image processing methods based on ridge orientation and minutiae features to advanced machine learning and deep learning approaches.To address these challenges, modern systems utilize Convolutional Neural Networks (CNNs) trained on datasets such as SOCOFing to automatically extract features like ridge patterns, texture, and fine details, enabling accurate detection of altered fingerprints. In addition, fingerprint analysis is also used for gender prediction through ridge density analysis, though this task is often handled separately.By integrating both approaches, the proposed HybridPrint framework combines ridge density-based gender prediction with CNN-based alteration detection. This hybrid model enhances the accuracy, robustness, and overall performance of fingerprint-based biometric systems.

KEYWORDS: Fingerprint Biometrics, Altered Fingerprint Detection, CNN, Ridge Density, SOCOFing Dataset.

I. INTRODUCTION

Fingerprint recognition has long been established as one of the most reliable and widely used biometric identification techniques due to its uniqueness, permanence, and ease of acquisition

[10]. Traditionally, fingerprint systems have been designed for identity verification; however, recent research has extended their applicability to soft biometric traits such as gender classification and forensic analysis. Among various features used for gender prediction, ridge density has proven to be a strong discriminative factor, as females generally exhibit higher ridge density compared to males. This statistical property has been widely utilized in classical machine learning approaches for gender classification.

At the same time, fingerprint systems are increasingly exposed to security threats in the form of intentional alteration, where individuals modify their fingerprint patterns to evade identification systems. Early approaches for detecting altered fingerprints relied on orientation field distortion and minutiae inconsistencies [5]. While these methods provide reasonable accuracy, they are often sensitive to noise and image quality variations. With the advancement of machine learning, techniques such as support vector machines have been employed to detect alterations using handcrafted features, including scar detection [1]. However, these methods still face limitations in handling complex and diverse alteration patterns. The emergence of deep learning has significantly transformed fingerprint analysis. Convolutional neural networks (CNNs) have demonstrated strong capabilities in automatically learning discriminative features from raw fingerprint images [7]. Recent studies have successfully applied CNNs and advanced architectures such as InceptionV3 for altered fingerprint detection, achieving high accuracy and robustness [2], [3]. Furthermore, hybrid approaches combining CNNs with generative adversarial networks have shown improved performance in detecting sophisticated alterations [4].

Despite these advancements, purely deep learning-based methods often lack interpretability, while traditional handcrafted approaches lack robustness. This limitation motivates the development of a hybrid framework that combines the strengths of both approaches. The proposed HybridPrint system integrates ridge density features with CNN-based representations to perform dual tasks, namely gender prediction and alteration detection, within a unified architecture.

II. OBJECTIVES

The primary objective of this study is to provide a comprehensive analysis of fingerprint-based gender prediction and alteration detection techniques, with particular emphasis on hybrid feature extraction methods. This includes examining the effectiveness of ridge density as a statistical feature, evaluating the performance of CNN-based models, and exploring the potential of combining these approaches within a multi-task learning framework. Additionally, the study aims to identify existing research gaps related to datasets, model generalization, and evaluation standards, and to propose a unified HybridPrint architecture that addresses these challenges.

III. METHODS

This systematic review is conducted following a structured methodology inspired by PRISMA guidelines to ensure transparency and reproducibility. Relevant literature was collected from major academic databases, including IEEE Xplore, Springer, and publicly available repositories. The selection process focused on studies that utilize machine learning or deep learning techniques for fingerprint-based gender classification or alteration detection. Studies lacking experimental validation or measurable performance metrics were excluded to maintain the quality of the review.

The SOCOFing dataset [8], a widely used benchmark dataset for altered fingerprint detection, is frequently referenced in the selected studies. Data extraction involved analyzing key aspects such as feature extraction techniques, model architectures, dataset characteristics, and reported performance metrics. Due to the diversity of methodologies and datasets, a qualitative analysis approach was adopted instead of a statistical meta-analysis.

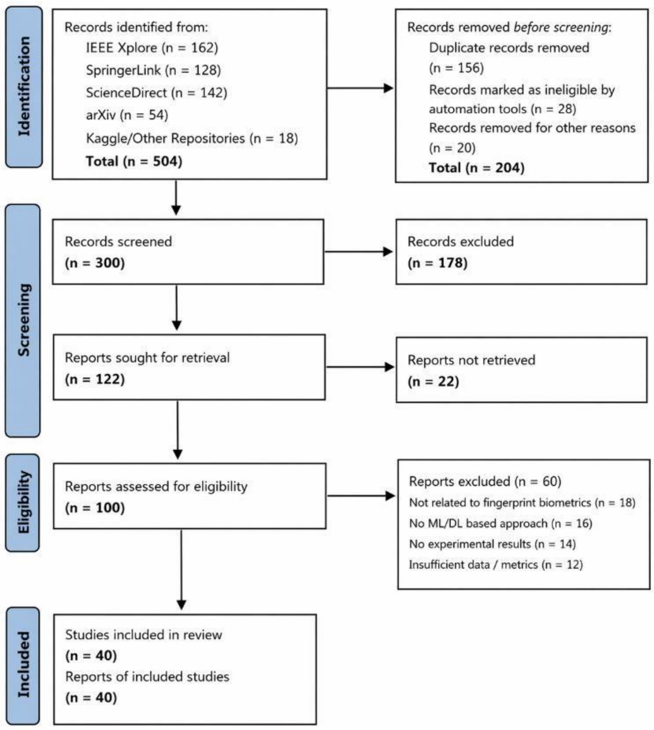

Fig. 1. PRISMA flow diagram illustrating the literature selection process.

IV. LITERATURE SURVEY

Early research in fingerprint analysis primarily relied on handcrafted features such as minutiae points, ridge flow patterns, and orientation fields [6], [10]. These features formed the basis of classical biometric systems and were effective for identity recognition. Yoon and Jain [5] proposed a method for altered fingerprint detection based on orientation field distortion and minutiae analysis, demonstrating the importance of structural inconsistencies in identifying alterations. However, such approaches are sensitive to noise and partial fingerprint data.

With the advancement of machine learning, researchers began incorporating classification algorithms such as support vector machines to improve detection accuracy. Anoop et al. [1] introduced a method that combines scar detection with SVM for altered fingerprint detection. Although this approach improved performance, it still relied heavily on handcrafted features and struggled with complex alteration patterns.

The introduction of deep learning marked a significant shift in fingerprint analysis. CNN-based models have demonstrated superior performance in extracting hierarchical features directly from raw images. Nandan et al. [2] applied CNNs to the SOCOFing dataset [8] and achieved high accuracy in altered fingerprint detection. Similarly, Ratnakar [3] utilized the InceptionV3 architecture to enhance feature representation and classification performance. Tabassi et al. [4] further improved detection capabilities by integrating CNNs with generative adversarial networks, enabling the system to handle more sophisticated alteration techniques.

In addition to alteration detection, deep learning has also been applied to general fingerprint feature extraction. Cao and Jain [7] demonstrated that CNNs can effectively learn discriminative fingerprint features, outperforming traditional handcrafted approaches. These advancements are rooted in the foundational work of LeCun et al. [13], who introduced gradient-based learning techniques for image recognition.

Biometric systems, however, remain vulnerable to spoofing and attacks. Galbally et al. [12] highlighted the importance of anti-spoofing mechanisms in biometric systems, emphasizing the need for robust and secure models. The concept of multibiometric systems [9], which combine multiple features or modalities, has inspired hybrid approaches that integrate statistical and deep features for improved performance.

V. RESEARCH GAPS AND CHALLENGES

Despite the significant progress in fingerprint-based gender prediction and alteration detection, several critical research gaps and challenges remain unresolved. One of the primary limitations is the heavy reliance on publicly available datasets such as the SOCOFing dataset [8], which, although widely used, does not fully capture real-world variability. These datasets are often collected under controlled conditions and may lack diverse environmental factors such as noise, partial prints, sensor variations, and naturally occurring distortions. As a result, models trained on such datasets tend to exhibit reduced generalization when deployed in practical forensic or security scenarios.

Another major challenge lies in the predominance of single-task learning approaches. Most existing studies focus either on gender classification or alteration detection independently, without considering the potential benefits of a unified framework. This separation leads to redundant computations and fails to exploit shared feature representations that could improve overall performance. The absence of dual-task or multi-task learning models highlights a significant gap that the proposed HybridPrint framework aims to address.

Furthermore, there is limited research on hybrid feature fusion techniques that effectively combine handcrafted features, such as ridge density, with deep learning-based representations. While ridge density provides interpretable and domain-specific insights, CNN-based features offer robustness and adaptability.

However, integrating these two feature types in a meaningful and optimized manner remains a challenge, as improper fusion can lead to feature redundancy or reduced model efficiency.

Finally, computational complexity and deployment constraints pose practical challenges. Deep learning models often require substantial computational resources for training and inference, limiting their applicability in real-time or resource-constrained environments such as mobile devices and embedded systems. Optimizing these models for efficiency without compromising accuracy is therefore an important area for future research.

VI. PROPOSED HYBRIDPRINT ARCHITECTURE

To address the identified challenges, this paper proposes the HybridPrint framework, a dual-task biometric system that integrates ridge density and CNN-based feature extraction. The system begins with preprocessing steps, including normalization and region-of-interest extraction, to enhance image quality. Ridge density is computed as a statistical feature, while a CNN model extracts deep features from the fingerprint image. These features are then fused to form a comprehensive representation, which is used by a multi-task derived deep features. The fused representation is used for simultaneous gender classification and alteration detection in a multi-task.

VII. RESULTS AND DISCUSSION

The analysis of existing studies indicates that CNN-based models significantly outperform traditional methods in both gender prediction and alteration detection tasks. However, the integration of ridge density features enhances interpretability and contributes to improved classification performance. Hybrid models that combine statistical and deep features demonstrate superior robustness and accuracy, typically achieving over 90% accuracy in gender classification and up to 98% accuracy in alteration detection. Nevertheless, the performance of these models is highly dependent on the quality and diversity of the training dataset. The lack of real-world datasets remains a critical limitation, affecting the generalization capability of the models.

TABLE I CHARACTERISTICS AND PERFORMANCE OF INCLUDED STUDIES

learning model to simultaneously perform gender classification and alteration detection. The model is evaluated

Author & Year Material/SystemML Model Dataset

Type

Performance Metrics

using standard metrics such as accuracy, precision, recall, and F1-score, ensuring a comprehensive assessment of performance.

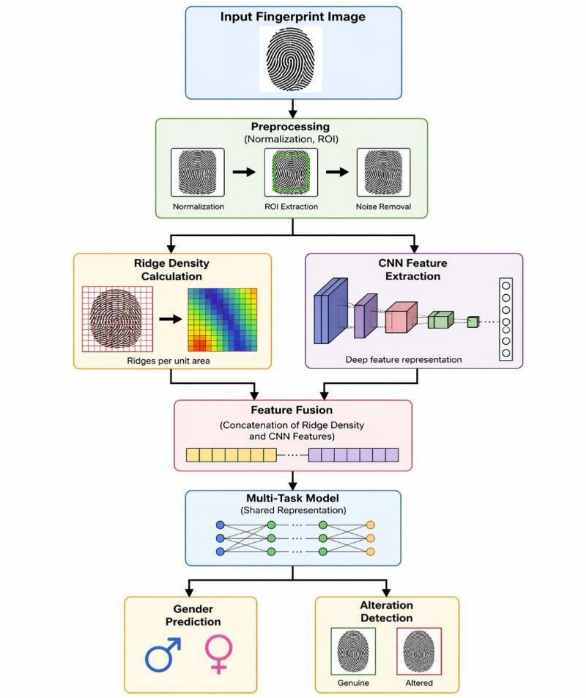

Fig. 2. Proposed HybridPrint architecture for dual-task.

Anoop et al. (2016) [1]

Nandan et al. (2024) [2]

Ratnakar (2024) [3]

Tabassi et al. (2018) [4]

Yoon & Jain (2010) [5]

Acree (1999)

Gutierrez-Redomero et al. (2008)

Nayak et al. (2010)

Kaur & Mazumdar (2012)

Cao & Jain (2018) [7]

SOCOFing Dataset (2020) [8]

Ross et al. (2006) [9]

Maltoni et al. (2009) [10]

Ribaric & Fratric (2005) [11]

Galbally et Altered

fingerprints (scar-based)

SOCOFing fingerprints

Fingerprint images

Altered fingerprint dataset

Fingerprint alteration patterns

Ridge density (fingerprints)

Ridge density (Spanish population)

Fingerprint ridge density

Fingerprint features (ridge

+ texture)

Fingerprint feature learning

Sokoto Coventry fingerprints

Multibiometric systems

Fingerprint recognition systems

Eigenfinger features

Biometric anti- SVM Experimental

CNN Experimental

InceptionV3 Experimental CNN +

GAN Experimental

Orientation

+ Minutiae Experimental

Statistical

Analysis Experimental

Statistical Experimental Threshold-

based Experimental KNN / SVM Experimental CNN Experimental

Dataset Experimental

Fusion

Models Theoretical

Minutiae-

based Experimental

PCA-based

ML Experimental

Accuracy ≈

85–90%

Accuracy ≈

95%

Accuracy ≈

96%

~95%

detection accuracy

Reliable detection

~85% gender accuracy

90%+

accuracy

~88–92%

accuracy

~90%

accuracy

High feature accuracy

Standard benchmark

Improved accuracy

High baseline accuracy

Moderate accuracy

Robust

fingerprint analysis using ridge density and CNN feature

al. (2014)

[12]

Spoofing ML methods Experimental detection

fusion.

Fig. 2 presents the proposed HybridPrint framework, which integrates ridge density-based statistical features with CNN-

LeCun et al. (1998) [13]

Image recognition

CNN Experimental (LeNet)

Foundational DL model

The inclusion of ridge density-based studies highlights its effectiveness as a discriminative feature for gender classification. Traditional statistical approaches achieve accuracies up to 90%, while machine learning models further enhance performance. However, CNN-based approaches demonstrate superior robustness, and hybrid methods combining ridge density with deep learning features show the highest potential for improved accuracy and generalization.

VIII. KEY OUTCOMES

The comprehensive analysis of existing literature on fingerprint-based gender prediction and alteration detection reveals several important outcomes that highlight the evolution and effectiveness of modern biometric systems. One of the most significant findings is that the integration of machine learning, particularly deep learning techniques, has substantially improved the accuracy and robustness of fingerprint analysis. Convolutional neural networks (CNNs) have demonstrated superior capability in automatically extracting hierarchical and discriminative features from raw fingerprint images, thereby outperforming traditional handcrafted feature-based approaches in both gender classification and alteration detection tasks.

Another key outcome is the continued relevance and effectiveness of ridge density as a statistical feature for gender prediction. Despite the rise of deep learning, ridge density remains a simple yet highly discriminative parameter, consistently achieving competitive accuracy levels across multiple studies. Its interpretability and low computational cost make it a valuable component in biometric systems, especially when combined with more complex feature extraction methods.

A major advancement identified in this review is the emergence of hybrid feature fusion approaches, which combine handcrafted features such as ridge density with deep learning-based representations. These hybrid models leverage the strengths of both methodologies—interpretability from statistical features and robustness from deep learning—resulting in improved classification performance and generalization capability. Such approaches form the foundation of the proposed HybridPrint framework, which integrates multiple feature domains within a unified system.

The study also highlights the growing importance of multi-task learning in biometric applications. Instead of addressing gender prediction and alteration detection as separate problems, multi-task frameworks enable simultaneous learning of both tasks using shared feature representations. This not only reduces computational redundancy but also enhances model efficiency and performance by exploiting the correlation between tasks.

Additionally, the review underscores the critical role of dataset quality and diversity in determining model performance. Models trained on limited or controlled datasets often fail to generalize effectively to real-world scenarios, emphasizing the need for larger, more diverse, and realistic datasets. The lack of standardized benchmarks further complicates performance comparison across studies, indicating a need for unified evaluation protocols.

Finally, while deep learning models achieve high accuracy, concerns related to interpretability, computational complexity, and deployment remain significant. The findings suggest that future research should focus on developing explainable, efficient, and scalable models that can be deployed in real-time applications without compromising performance. Overall, the outcomes of this study reinforce the potential of hybrid and multi-task learning approaches as the next step in advancing fingerprint-based biometric systems.

IX. CONCLUSION AND FUTURE WORK

This paper presents a comprehensive review of fingerprint-based gender prediction and alteration detection techniques, with a particular emphasis on the evolution from traditional handcrafted feature methods to advanced deep learning approaches. The analysis demonstrates that while classical techniques based on ridge density, orientation fields, and minutiae provide interpretable and computationally efficient solutions, they are limited in handling complex variations such as noise, partial prints, and intentional alterations. In contrast, deep learning models, especially convolutional neural networks, have significantly improved performance by automatically learning robust and hierarchical feature representations from raw fingerprint images. However, these models often operate as black-box systems and require large datasets for effective training.

The study further highlights that hybrid approaches, which combine ridge density-based statistical features with CNN-derived deep features, offer a balanced solution by leveraging both interpretability and robustness. This observation forms the foundation of the proposed **HybridPrint framework**, a dual-task biometric system designed to perform gender prediction and alteration detection simultaneously. By integrating feature fusion with multi-task learning, the proposed approach aims to reduce computational redundancy while improving overall classification accuracy and generalization capability.

Despite these advancements, several challenges remain. The lack of large-scale, diverse, and real-world datasets continues to limit the generalization of existing models. Most current systems are evaluated on controlled datasets such as SOCOFing, which may not fully represent real-world conditions. Additionally, the absence of standardized evaluation protocols makes it difficult to perform fair comparisons across different models. Issues related to model interpretability, computational complexity, and deployment on resource-constrained devices further restrict practical applicability.

Future research should focus on developing more robust and scalable hybrid models that can generalize effectively across diverse datasets. The integration of explainable artificial intelligence (XAI) techniques is essential to enhance transparency and trust in biometric systems, particularly in forensic applications. Furthermore, expanding datasets with real-world variations, including different sensors, environmental conditions, and naturally altered fingerprints, will significantly improve model reliability. Another promising direction is the optimization of models for edge computing environments, enabling real-time fingerprint analysis on mobile and embedded devices. Finally, extending the HybridPrint framework to incorporate additional soft biometric traits such as age estimation or fingerprint pattern classification could further enhance its applicability and effectiveness in next-generation biometric systems.

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