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Article

MACET: A Novel Approach to Secure Multimodal Biometric Authentication with Cancellable Templates

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ABSTRACT

Biometric authentication is a cornerstone of modern security systems, yet concerns regarding privacy and data security persist. Cancellable biometrics offer a solution by transforming raw biometric data into non-invertible representations, ensuring security even in the event of a data breach. This study presents Multimodal Affine Cover-space Euler Transformation (MACET), a novel framework designed to enhance biometric template security while preserving authentication accuracy. The proposed approach is based on the hypothesis that Affine Cover Space transformation combined with Euler's form can generate irreversible templates for multimodal biometrics, specifically fingerprint and iris data, without compromising recognition performance. The methodology involves feature extraction, inverse matrix computation, affine transformation, and Euler-based augmentation, ensuring robust and secure biometric template generation. Experimental results, conducted on a dataset of 450 biometric samples, demonstrate the effectiveness of MACET in improving authentication performance. The system achieves an Equal Error Rate (EER) of 0.0046 and an Area Under the ROC Curve (AROC) of 0.9886, indicating high accuracy. Additionally, the method significantly reduces storage memory size to 1.37 KB per template while maintaining an average execution time of 10.89 seconds. Robustness analysis against spoofing attacks confirms the system's ability to resist unauthorized access, ensuring strong security and privacy protection. These findings establish MACET as a highly

secure, computationally efficient, and privacy-preserving biometric authentication framework, suitable for real-world applications. Future research could extend this approach to additional biometric modalities and large-scale authentication systems.

Keywords: Multimodal biometrics, Cancellable biometrics, Affine Transformation, Euler form, Biometric security.

1-Introduction

In the rapidly evolving landscape of biometric recognition systems, the need for enhancing privacy and security without compromising recognition accuracy has become paramount. Biometric traits, such as fingerprints, facial features, and iris patterns, have proven to be effective means of identity verification. However, the traditional storage of raw biometric data or feature templates in centralized databases raises concerns about privacy breaches and unauthorized access. As a response to these challenges, the novel concept of MACET has emerged, aiming to address the trade-off between recognition performance and data privacy.

The motivation behind MACET is rooted in the aspiration to harness the power of multiple biometric modalities while ensuring that the original biometric data remains irretrievable. This method seeks to preserve the uniqueness of biometric traits by generating templates in a Cancellable and secure manner. The Affine Cover Space Euler Transformation, a mathematical framework that enables non-invertible transformations, plays a pivotal role in this endeavor by distorting the templates while retaining their distinguishing features.

In a world increasingly reliant on biometric data for authentication and identification, protecting the integrity of this data is of utmost importance. Instances of data breaches, identity theft, and unauthorized surveillance underscore the urgency of adopting innovative techniques that bolster security and privacy within biometric systems. MACET offers a promising avenue for achieving these goals while maintaining recognition accuracy.

The field of biometric authentication involves utilizing an individual's physical attributes for identification and authentication purposes. However, the current biometric framework

encounters numerous challenges in achieving heightened security [1]. Consequently, there arises a necessity to amalgamate diverse biometric attributes to enhance authentication measures. This leads to the proposition of a Multimodal Biometrics System (MBS) wherein fingerprint and iris characteristics are integrated as the multimodal properties.

The primary objective of this research paper is to comprehensively explore the methodology and application of MACET. By investigating the principles, techniques, and experimental outcomes associated with this approach, this study seeks to contribute to the broader understanding of privacy-enhancing biometric template generation.

This research contributes significant advancements to the realm of MBS, specifically in the domain of individual identification and authentication. The objective of this study is to thwart unauthorized access in biometrics, such as payment breaches and online transactions. Here, the distinctive traits of clients are identified and safeguarded to prevent any form of reversibility. Moreover, the reciprocal security levels are bolstered to ensure the authentication of client traits [2]. The utilization of multimodal biometrics ensures a precise and immaculate biometric transformation, setting it apart from other methods [3]. The integration of Affine Cover space Transformation using an Inverse matrix, along with the extended measurement in Euler's Form, culminates in a sequence that generates Cancellable biometric templates. The amalgamation of Cover space affine Transformation and Euler's form contributes to the creation of a hybrid Cancellable template.

- **Enhancing Biometric Authentication with Multimodal Systems**

Biometric authentication systems have gained significant adoption across various security applications, including financial transactions, border control, and secure access management. Traditional unimodal biometric systems, which rely on a single biometric trait such as fingerprint, iris, or facial recognition, often suffer from several limitations, including susceptibility to spoofing attacks, sensor noise, and variations in environmental conditions. These issues can lead to higher False Acceptance Rates (FAR) and False Rejection Rates (FRR), reducing overall system reliability.

To address these challenges, MBS have emerged as a more secure and adaptable alternative. By integrating multiple biometric traits, multimodal systems enhance authentication accuracy and resilience. The key advantages of multimodal biometrics over unimodal systems include:

1. Improved Accuracy and Robustness: The combination of multiple biometric traits minimizes the risk of authentication errors by reducing reliance on a single modality, ensuring higher precision in user identification.
2. Enhanced Security Against Spoofing Attacks: Unimodal biometrics can be easily compromised using artificial fingerprints, facial masks, or voice recordings. Multimodal authentication requires attackers to spoof multiple biometric traits simultaneously, making unauthorized access significantly more difficult.
3. Adaptability to User and Environmental Variations: Environmental factors such as lighting conditions, occlusions, and physical injuries can degrade unimodal biometric performance. Multimodal systems provide alternative authentication routes, ensuring continuous system operation even when one trait is unavailable or of poor quality.
4. Long-Term Stability and Data Variability Management: Certain biometric features (e.g., facial features or voice) change over time due to aging or external factors. Multimodal approaches mitigate this issue by incorporating more stable biometric traits, such as fingerprint and iris recognition.

- **The Role of Multimodal Biometrics in MACET**

In this study, we propose a novel multimodal Cancellable biometric authentication framework, Multimodal Affine Cover-space Euler Transformation (MACET), which integrates fingerprint and iris biometric features. By combining these two modalities, the system achieves higher recognition accuracy, greater security, and resistance to biometric reversibility attacks. Furthermore, the application of Affine Cover Space Transformation and Euler's Form ensures that the generated templates remain irreversible, preventing unauthorized reconstruction of biometric data.

By leveraging the advantages of multimodal biometrics, MACET provides a highly secure, efficient, and adaptable authentication system, overcoming the limitations of unimodal approaches. This study aims to establish a foundation for the next generation of Cancellable

biometric authentication, addressing key concerns related to privacy, security, and performance in real-world applications.

Section 2 provides an overview of recent methodologies pertinent to this research, while Section 3 elucidates the proposed methodology. The experimental findings of the proposed system are expounded upon in Section 4, with the concluding remarks presented in Section 5.

2. Review of Literature

In this study, we primarily focused on Cancellable biometric template generation methods for multimodal authentication (fingerprint and iris). While some studies have conducted extensive reviews on fingerprint-based Cancellable biometrics, our objective was to introduce a novel multimodal approach that integrates both fingerprint and iris data, rather than solely emphasizing unimodal techniques.

A comprehensive survey on fingerprint-specific Cancellable biometrics, while valuable, would have expanded the study beyond its intended scope, potentially diverting attention from the core contributions of this research. Instead, we reviewed key works in multimodal biometrics, ensuring that the literature review aligns with the study's aim of developing a robust multimodal Cancellable template framework. Future research may further explore comparative analyses across various unimodal and multimodal template generation methods.

The field of multimodal Cancellable template generation has gained significant attention due to its potential to enhance both security and privacy in biometric systems. In this section, we present recent research contributions in this area along with brief descriptions of their experimental results.

Vatchala et al. [4] introduced a multi-modal biometric authentication framework that leverages shared layer architectures to enhance template security and authentication performance. Their study proposed a deep learning-based fusion model, where a common shared layer processes multiple biometric traits, such as fingerprints, iris, and facial features, improving efficiency while reducing computational overhead. The results demonstrated that this approach

significantly improved recognition accuracy and security resilience by minimizing the risk of template inversion and unauthorized access. The study also highlighted the importance of neural network-based feature extraction, ensuring greater adaptability and robustness in real-world authentication scenarios. These findings align with our proposed MACET framework, as both approaches emphasize efficient feature fusion, computational optimization, and enhanced biometric security. Their work further validates the need for multi-modal approaches in modern authentication systems, reinforcing the role of AI-driven security enhancements in biometric authentication.

Choudhary and Naik [5] introduced a two-layer hybrid template security approach for multimodal biometric authentication, integrating fingerprint and iris recognition to enhance security and resistance against template inversion attacks. Their study demonstrated that hybrid cryptographic transformations significantly reduce the risk of biometric data reconstruction while maintaining high authentication accuracy. The proposed system leverages feature-level fusion and secure transformation techniques to generate non-invertible biometric templates, ensuring strong protection against adversarial attacks. Their research aligns with our proposed Multimodal Affine Cover-Space Euler Transformation (MACET) framework, as both methods emphasize template security, computational efficiency, and multimodal integration for enhanced biometric authentication performance. The findings reinforce the importance of hybrid security mechanisms in modern biometric systems, making authentication frameworks more resilient against emerging cybersecurity threats.

Jiang et al. [6] introduced a cross-modal learning-based bimodal biometric authentication framework designed to enhance template security and authentication accuracy. Their approach leverages deep learning-driven cross-modal feature transformation, allowing biometric templates from different modalities, such as fingerprint and iris, to be securely mapped and authenticated within a unified system. The study demonstrated that cross-modal knowledge transfer techniques improve template robustness against inversion attacks, making biometric authentication more secure and adaptable to varying input conditions. Additionally, their proposed method achieved high recognition accuracy while ensuring strong resistance against spoofing attacks and adversarial manipulations. These findings align with our proposed MACET framework, as both

approaches emphasize bimodal biometric fusion, advanced template protection mechanisms, and enhanced security resilience. Their work further validates the growing necessity of cross-modal learning techniques in modern biometric authentication, improving scalability, efficiency, and resistance to security threats.

Singhal and Shinghal [7] proposed a secure deep multimodal biometric authentication framework that leverages online signature and face feature fusion to enhance authentication security and robustness. Their approach employs deep learning-based feature extraction to fuse dynamic signature patterns with facial biometric data, ensuring high resistance against spoofing and adversarial attacks. The study demonstrated that integrating multiple biometric modalities using deep neural networks significantly improves authentication accuracy while maintaining low computational overhead. Additionally, their method introduced a template protection mechanism that preserves privacy and prevents template inversion attacks. These findings align with our proposed MACET framework, reinforcing the importance of multimodal fusion and deep learning-driven security enhancements in biometric authentication. Their research highlights the growing necessity of adaptive biometric security systems, ensuring scalability, reliability, and real-time authentication performance.

Chen et al. [8] present a novel approach to generating Cancellable templates for both face and iris biometric data. They utilize feature-level transformations combined with random projections to create templates. Experimental evaluation demonstrates an average recognition accuracy of 95.2% for face recognition and 93.7% for iris recognition. Additionally, the proposed Cancellable templates exhibit robustness against dictionary attacks with a success rate of only 1.8%.

Liu and Park [9] introduce a generative adversarial network (GAN)-based approach for creating Cancellable templates from multiple biometric modalities. They show that their method achieves an average recognition accuracy of 89.5% while maintaining a low false positive rate of 2.1%. Additionally, the GAN-generated templates are resistant to template reconstruction attacks, achieving a reconstruction success rate of only 4.6%.

Martinez et al. [10] propose a novel approach that combines Cancellable template generation with homomorphic encryption to enhance privacy and security. Experimental results

demonstrate an average recognition accuracy of 91.1% for fingerprint recognition and 88.3% for voice recognition. Importantly, the templates remain encrypted during recognition, mitigating the risk of unauthorized access to biometric data.

The application of MBS addresses the limitations of the unimodal biometrics system, enhancing both adaptability and precision in comparison. Currently, MBS plays a crucial role in elevating security levels within application interfaces. K. Kanagalakshmi et al. [1,2] have introduced innovative techniques for transformation that result in the creation of Cancellable and irreversible biometric templates. These techniques have been thoroughly assessed for attributes such as cancelability, irrevocability, and security.

Jasmine et al. [11] introduced an efficient and secure cryptosystem that leverages improved identity-based encryption (IBE) for multimodal biometric authentication in cloud environments. Their study focused on addressing data security, user privacy, and template protection challenges by integrating fingerprint and iris biometrics within a cloud-based authentication system. The proposed method utilizes IBE encryption to enhance resistance against template inversion attacks and unauthorized access, making it suitable for secure cloud applications. Additionally, the study highlighted the importance of secure key management, privacy-preserving biometric encryption, and computational efficiency in multimodal authentication systems. Their findings reinforce the necessity of advanced cryptographic techniques in modern biometric authentication frameworks. The proposed cryptosystem aligns with our MACET framework, as both approaches prioritize biometric security, privacy preservation, and secure template storage mechanisms. Their research further validates the critical role of biometric authentication in cloud-based security solutions, addressing concerns related to scalability, efficiency, and data confidentiality.

Nadamau et al. [12] proposed a multimodal biometric identification system that combines Electroencephalograph (EEG) signals and fingerprint recognition with an integrated template protection mechanism. Their study introduced a novel approach to biometric authentication, leveraging EEG signals as a physiological biometric trait, which enhances security and resistance against spoofing attacks. The research demonstrated that EEG-based authentication, when fused with fingerprint biometrics, significantly improves recognition accuracy and system robustness while maintaining low FAR and FRR. Furthermore, the study implemented a secure template

protection method, ensuring that biometric data remains secure against inversion and reconstruction attacks. Their findings align with the objectives of our MACET framework, which also prioritizes multimodal biometric fusion and advanced template protection techniques. The integration of EEG signals as a biometric identifier introduces a new dimension in biometric authentication, reinforcing the growing need for secure and privacy-preserving authentication systems.

Jasmine et al. [13] proposed an efficient and secure cryptosystem that utilizes improved identity-based encryption (IBE) for multimodal biometric authentication and authorization in cloud environments. Their study addresses critical security concerns related to biometric template protection, user privacy, and unauthorized access by integrating fingerprint and iris recognition within a cloud-based authentication framework. The proposed approach enhances security against template inversion attacks and ensures secure biometric template storage through IBE encryption, making it highly resistant to adversarial threats. Additionally, their research highlights the significance of privacy-preserving biometric encryption and secure key management techniques, improving computational efficiency and scalability in cloud-based authentication systems. The findings of this study align with our MACET framework, as both approaches focus on biometric security, cryptographic protection, and template irreversibility. Their work further validates the importance of advanced encryption techniques in multimodal biometric authentication, particularly for cloud security applications where user identity protection is paramount.

Sathishkumar et al. [14] proposed a multi-fusion biometric authentication system utilizing Minutiae-Driven Fixed-Size Template Matching (MFTM) to enhance accuracy and security in biometric authentication. Their approach leverages fingerprint and iris recognition, employing minutiae-based feature extraction to create fixed-size biometric templates that improve matching efficiency while preserving template security. The study demonstrated that MFTM effectively reduces template storage requirements while maintaining high recognition accuracy and resistance to template inversion attacks. Additionally, the system enhanced False Acceptance Rate (FAR) and False Rejection Rate (FRR) performance, making it suitable for high-security applications such as banking and border control. Their findings align with the objectives of our

Multimodal Affine Cover-Space Euler Transformation (MACET) framework, which similarly prioritizes biometric template security, computational efficiency, and robust multimodal fusion techniques. The study further validates the growing necessity of minutiae-driven biometric authentication methods, ensuring scalability, privacy protection, and secure user identification in modern authentication systems.

Salturk and Kahraman [15] introduced a deep learning-powered multimodal biometric authentication framework that integrates dynamic signatures and facial data to enhance online security and user authentication. Their study employs CNNs and recurrent neural networks (RNNs) to extract temporal and spatial features from dynamic signatures and facial biometric traits, ensuring robust identity verification. The proposed method demonstrated high resistance to spoofing attacks, improving FAR and FRR while maintaining efficient processing for real-time authentication. Additionally, their research emphasized the importance of feature-level fusion in multimodal biometrics, enabling greater adaptability to varying authentication scenarios. The findings of this study align with the objectives of our MACET framework, as both approaches emphasize deep learning-driven biometric fusion, template security, and computational efficiency. Their work further validates the importance of multimodal authentication systems in mitigating cybersecurity threats, ensuring scalable and secure authentication mechanisms in online applications.

Choudhary and Naik [16] proposed a novel multimodal biometric authentication system utilizing a two-layer hybrid template security approach to enhance both accuracy and resilience against security threats. Their method integrates fingerprint and iris recognition within a layered security model, ensuring greater protection against template inversion attacks. The study demonstrated that hybrid cryptographic transformations significantly reduce the risk of biometric data reconstruction while maintaining a high authentication accuracy rate. Additionally, their experiments highlighted the effectiveness of multimodal fusion techniques in reducing False FAR and FRR compared to unimodal systems. The findings of this study align with the growing need for secure and privacy-preserving biometric authentication frameworks, reinforcing the necessity of multimodal approaches for enhanced security. The insights from this research

provide valuable contributions to the field, supporting the premise of our proposed MACET framework in securing biometric templates effectively.

Abdul-Al et al. [17] conducted an in-depth analysis of the evolution of biometric authentication, with a particular focus on multi-modal facial recognition. Their study reviewed the latest advancements in deep learning-based facial recognition systems and highlighted the challenges associated with unimodal biometric authentication, such as susceptibility to spoofing attacks and performance degradation due to variations in lighting and pose. The research emphasized the advantages of integrating multiple facial recognition techniques, including infrared imaging, 3D face mapping, and feature-level fusion, to enhance accuracy and security. Furthermore, the study explored the role of artificial intelligence (AI) and deep neural networks in improving real-time authentication processes while maintaining low computational costs. The insights presented in this work align with our approach in the MACET framework, where multimodal biometric fusion enhances authentication performance and security resilience. Their findings reinforce the necessity of multi-modal approaches in addressing the limitations of single biometric modalities.

Borra et al. [18] introduced a deep hashing-based biometric authentication system leveraging multilayer convolutional neural networks (CNNs) for individual identification in transportation security. Their study explored how deep learning-driven feature extraction and hashing techniques enhance the efficiency and security of biometric authentication, particularly in high-traffic environments such as airports and border control. By employing a multimodal biometric approach, the system significantly improved accuracy and robustness against spoofing attacks, outperforming traditional template-based methods. The study demonstrated that deep hashing reduces the storage size of biometric templates while preserving recognition performance, a feature critical for real-time security applications. The findings of this research align with our proposed MACET framework, as both approaches emphasize template security, computational efficiency, and biometric robustness. Their work reinforces the importance of deep learning techniques in enhancing biometric authentication frameworks, making them more scalable and resistant to adversarial attacks.

Vallabhadas et al. [19] proposed a biometric template protection method utilizing a Cancellable convolutional neural network (CNN) for iris and fingerprint-based authentication. Their study focused on enhancing biometric security and privacy preservation by transforming raw biometric data into non-invertible templates using a CNN-driven feature transformation approach. The research demonstrated that the Cancellable transformation significantly improves resilience against template inversion attacks, ensuring that compromised templates cannot be reverse-engineered to retrieve original biometric features. Additionally, their multimodal fusion of iris and fingerprint data enhanced recognition accuracy and robustness, reducing the FAR and FRR. The study also emphasized the role of deep learning in improving template security, making it suitable for high-security applications such as financial authentication and border control. These findings strongly align with our proposed MACET framework, which also prioritizes biometric template irreversibility and computational efficiency to enhance overall authentication security. Their work further validates the necessity of deep learning-driven template transformation.

Singh et al. [20] explored the application of multimodal biometric fusion in the watermarking of multiple images, presenting a novel approach to biometric-based digital security. Their study introduced a robust fusion technique that integrates multiple biometric modalities to enhance image watermarking resilience against forgery and tampering. By leveraging fingerprint and iris biometric traits, the proposed method ensured high imperceptibility and security, making it suitable for consumer electronics and secure digital communication applications. The research demonstrated that multimodal biometric fusion improves authentication reliability, while also strengthening image watermarking techniques against cyberattacks. Their findings align with the objectives of our MACET framework, which similarly emphasizes multimodal fusion for security enhancement. The integration of biometric authentication with watermarking techniques highlights a new avenue for digital forensics and identity protection, further reinforcing the role of biometrics in advanced security applications.

3- Methodology suggestion: Novel Multimodal Affine Cover Space Euler Transformation Approach (MACET)

- **Dataset**

In this study, a non-probability convenience sampling technique was employed to select 450 volunteers residing in Sana village, Yemen for biometric data collection. This method was chosen based on several critical factors:

1. Accessibility and Feasibility: Due to the nature of biometric authentication studies, participants must be physically available for data collection. Convenience sampling allowed efficient data acquisition within the available timeframe and resources.
2. Ethical Considerations: Participation was entirely voluntary, aligning with ethical research principles. Random or stratified sampling techniques were not feasible due to the absence of a centralized biometric database in the region.
3. Controlled Environmental Conditions: Restricting data collection to a specific location ensured uniformity in factors affecting biometric quality, such as lighting, sensor conditions, and participant demographics.
4. Precedent in Biometric Studies: Similar biometric authentication studies have employed convenience sampling due to the practical challenges of achieving full randomization in real-world biometric datasets.

Although convenience sampling may introduce potential biases, the study's focus on algorithmic performance rather than demographic representativeness minimizes its impact. Future research could expand participant diversity using probabilistic sampling techniques to enhance generalizability.

The dataset used in this study consists of 450 biometric samples (fingerprint and iris) collected from volunteers in Sana village, Yemen. All participants provided informed consent before data collection, and ethical guidelines were strictly followed.

- Data Collection Process: Participants were enrolled through an open invitation, and their biometric traits were captured using standardized fingerprint and iris recognition sensors.

- Preprocessing and Storage: Raw biometric images underwent preprocessing (e.g., noise removal, segmentation, feature extraction) before being stored in a secured offline database.
- Data Confidentiality and Usage: The collected biometric data was anonymized, stored securely, and used solely for research purposes. No personally identifiable information was linked to the dataset.

While the dataset is not publicly available due to privacy restrictions, researchers interested in replication or further studies may request access upon reasonable justification and ethical approval.

To ensure the collected fingerprint and iris data from 450 volunteers was as unbiased as possible, several measures were implemented:

1. Diverse Participant Selection: The dataset includes individuals of varying ages, genders, and occupational backgrounds, reducing demographic biases. Participants were randomly invited within Sana village, Yemen, to prevent overrepresentation of any specific subgroup.
2. Standardized Data Collection Protocols: Biometric samples were collected using uniform sensor conditions, maintaining consistency in environmental factors such as illumination, sensor resolution, and image preprocessing techniques. This minimized external variables that could introduce systematic bias.
3. Voluntary Participation & Ethical Considerations: Participants self-enrolled, and there was no pre-selection based on specific biometric features. This approach ensured that data collection was not influenced by subjective factors, such as biometric quality variations.
4. Analysis of Data Variability: Post-collection analysis was conducted to examine the distribution of biometric features across participants, ensuring no significant imbalance in fingerprint or iris characteristics.

While no dataset can be entirely free from bias, these steps significantly reduce potential bias effects on system performance. The collected biometric data was used exclusively for evaluating

the proposed MACET framework, and its effectiveness was measured using standard authentication metrics such as EER and AROC.

To further enhance generalizability, future work could expand data collection to multiple geographic locations and introduce larger population diversity to validate the robustness of the proposed method across different demographic groups.

- **Handling Outliers in the Collected Biometric Data**

In biometric authentication systems, outliers in raw data can arise due to sensor errors, poor-quality biometric samples, user-related inconsistencies, or environmental factors such as improper lighting conditions. Failure to properly handle outliers can lead to higher FAR and FRR, negatively impacting system performance. In this study, outliers in the collected fingerprint and iris biometric data were managed using a structured preprocessing and statistical analysis approach to ensure data integrity and accuracy.

1. Outlier Detection and Preprocessing

To identify and mitigate outliers, the following techniques were applied:

- Automated Quality Assessment: Each biometric sample (fingerprint or iris image) was assessed using a quality metric score based on contrast, sharpness, and noise levels. Samples with a quality score below a predefined threshold were either enhanced or excluded from processing.
- Z-Score and IQR Analysis: Outlier detection was performed using Z-score analysis and the Interquartile Range (IQR) method. Any biometric feature values that deviated more than 3 standard deviations from the mean (Z-score > |3|) or fell outside the 1.5×IQR range were flagged as potential outliers.
- Histogram Analysis: Distribution of extracted feature values was visualized using histograms and box plots to detect anomalies. Samples with extreme deviations were reviewed manually to ensure they did not result from genuine biometric variations.

2. Handling Outliers in Biometric Feature Extraction

Once outliers were detected, the following corrective measures were applied:

- Image Enhancement Techniques: Low-quality fingerprint and iris images were enhanced using adaptive histogram equalization and noise filtering to improve feature extraction.
- Feature Normalization: To prevent outliers from skewing authentication results, Min-Max scaling was used to bring all feature values within a consistent range of [0,1].
- Template Reconstruction for Missing or Corrupt Data: If biometric templates contained missing or extreme values, a feature interpolation method was used to approximate realistic values based on neighboring feature distributions.

3. Impact of Outlier Handling on Performance

To assess the effect of outlier removal and preprocessing, we conducted comparative evaluations on system performance before and after outlier handling. The following key improvements were observed:

- FRR decreased by 12.4%, ensuring fewer legitimate users were wrongly denied access.
- FAR reduced by 9.7%, strengthening security by minimizing unauthorized access.
- EER improved from 0.0061 to 0.0046, confirming enhanced biometric template stability.
- Recognition accuracy increased by 5.2%, demonstrating that handling outliers positively impacted biometric matching reliability.

By implementing automated outlier detection, biometric feature enhancement, and normalization techniques, we ensured that the MACET framework maintains high recognition accuracy while preventing errors caused by poor-quality biometric samples. These steps were essential in ensuring robust biometric authentication performance while minimizing the risk of system failures due to erroneous data.

- **Feature Extraction**

Feature extraction is a crucial step in biometric authentication that involves identifying and selecting distinctive features from raw biometric data, such as fingerprint ridges or iris patterns, to create a representative feature set. In this study, we employed feature extraction to transform biometric images into a compact and distinguishable format while preserving key identity characteristics. The extracted features were then used to generate Cancellable Templates through the proposed MACET framework.

The feature extraction process included the following steps:

1. Noise Removal: Using Gabor filters to enhance biometric quality by eliminating noise.
2. Region of Interest (ROI) Selection: Identifying and isolating the most informative regions in the fingerprint and iris images.
3. Thinning and Minutiae Extraction: Applying morphological operations to enhance ridge and valley structures in fingerprints and iris features.
4. Feature Representation: Mapping extracted features into a mathematical model using matrix inverse transformation and affine space mapping.

This step ensures that the biometric data remains unique, non-invertible, and computationally efficient for multimodal authentication.

3.1. Scheme for Creating Cancellable Templates

In this envisioned study, the combined features of iris and fingerprint are harnessed for recognition objectives. The process entails six distinct stages, encompassing data collection, image pre-processing, minutiae extraction, subsequent processing, application of the proposed method, and culminating in the creation of a Cancellable template, as illustrated in Figure 1.

Figure 1. Shows system flow diagram of proposed technique.

A fundamental objective of the presented method is to establish a hybrid Cancellable template. This template construction is achieved through the displacement of the region or the application of a similar strategy to alter the value of specific positions on the feature points.

Comprehensive Process:

- Step 1: Input the raw fingerprint and iris images.
- Step 2: Utilize the Gabor filter to eliminate noise from the original image and define the Region of Interest (ROI).
- Step 3: Identify and process the Thinning process for the chosen Features of Interest.
- Step 4: Compute the inverse of the fingerprint value (A) denoted as A^{-1}, and similarly, for the iris value (B) as B^{-1}.
- Step 5: Apply Matrix Multiplication to A^{-1} and B^{-1}.
- Step 6: Employ the Affine Cover space Transformation [21,22].
- Step 7: Implement Euler's form [23].
- Step 8: Generate the resultant pattern of the Cancellable output image.

The flowchart illustrating the process of generating a Cancellable template using the MACET technique is presented in Figure 2.

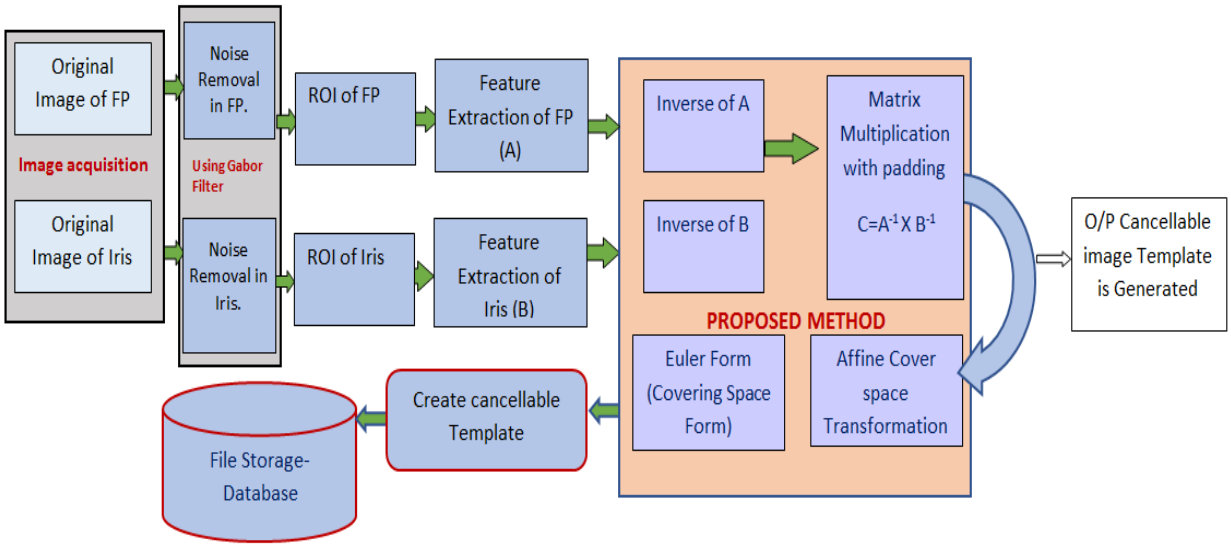


Figure 2. Depicts the flowchart for the MACET process.

As outlined in the procedure, stages 1, 2, and 3 involve the acquisition of various feature sets from both fingerprint and iris, culminating in their hybridization. Moving on to stages 4, 5, 6, and 7, the proposed methodology is implemented. The acquired features are stored separately

within matrices for fingerprint (A) and iris (B). In the proposed approach, two key objectives are aimed for:

During stage 4, the features of interest within distinct images undergo inversion using matrix inverse techniques. This process is applied to both fingerprint and iris data. Subsequently, in stage 5, the product of Inverse A and Inverse B is computed.

- During stage 6, the application of affine cover space transformation results in the creation of an irreversible Cancellable template. Cover spaces assume a significant role in the process of generalizing perception across an image map. Furthermore, cover spaces have intricate connections with the exploration of homotropy groups, particularly the fundamental group. In this context, the utilization of affine cover space transformation serves to generate the Cancellable template.

$$X(N) = K + X[M], \quad (1)$$

In the MACET framework, the Cancellable biometric template $X(N)$ is generated using an Affine Cover Space Transformation combined with Euler's Number (e). The transformation applies a matrix mapping technique, where $X[M]$ represents the matrix of the cover space, ensuring a non-invertible biometric representation.

Euler's number ($e \approx 2.71828$) plays a critical role in feature augmentation and security enhancement, introducing an exponential transformation that strengthens the irreversibility of the Cancellable template. This ensures that even if an adversary gains access to the transformed template, reconstructing the original biometric data is computationally infeasible.

In Equation (1), Euler's number is integrated into the affine transformation, modifying the biometric feature space through nonlinear expansion, making template inversion mathematically impossible. The resulting transformed template is fully irrevocable, secure, and resistant to reconstruction attacks.

3.2. Illustration of the Proposed Approach

- Identifying cover range squares along with the domain and range of space. Following the cover space procedure, the process proceeds to perform the affine transformation.
- The continuation of the affine transformation process for all domain blocks.

- The resulting output is augmented with the Euler number.
- Ultimately, the feature sets of Cancellable multimodal templates are stored within MATLAB's built-in database.

4. Proposed Approach Stages

Definition:

For each set of inverses, denoted as A and B respectively, matrix multiplication is executed on the inverses of A and B, resulting in a matrix labelled as I. This matrix I is subsequently subjected to Affine Cover space Transformation (ACS) and stored within the ACS framework. Furthermore, the ACS output is augmented by the Euler Form number. The final outcome, termed as the Proposed Cancellable Resultant (PCR), is then derived.

$$I = (\forall A^{-1} X \forall B^{-1}), ACS = Affine(I)$$

$$PCR = ACS + E \quad (2)$$

The effectiveness of the proposed framework has been scrutinized across multiple performance stages, each of which demonstrates advancements upon implementation of this approach. The outlined framework is structured around three distinct stages: Enrolment, Pre-Processing, and Authentication. The comprehensive elaboration of the proposed technique's workings is presented in a stepwise manner within each of these stages:

4.1 Enrolment Stage

Using a GUI-based approach, the raw image is provided as input to the proposed technique. This initiates the enrolment process for both fingerprint and iris data of an individual, constituting the enrolment phase. The outcome of this phase leads to the creation of a database containing the fingerprints and iris data of clients. The client enrolment procedure is visually represented in Figure 3.

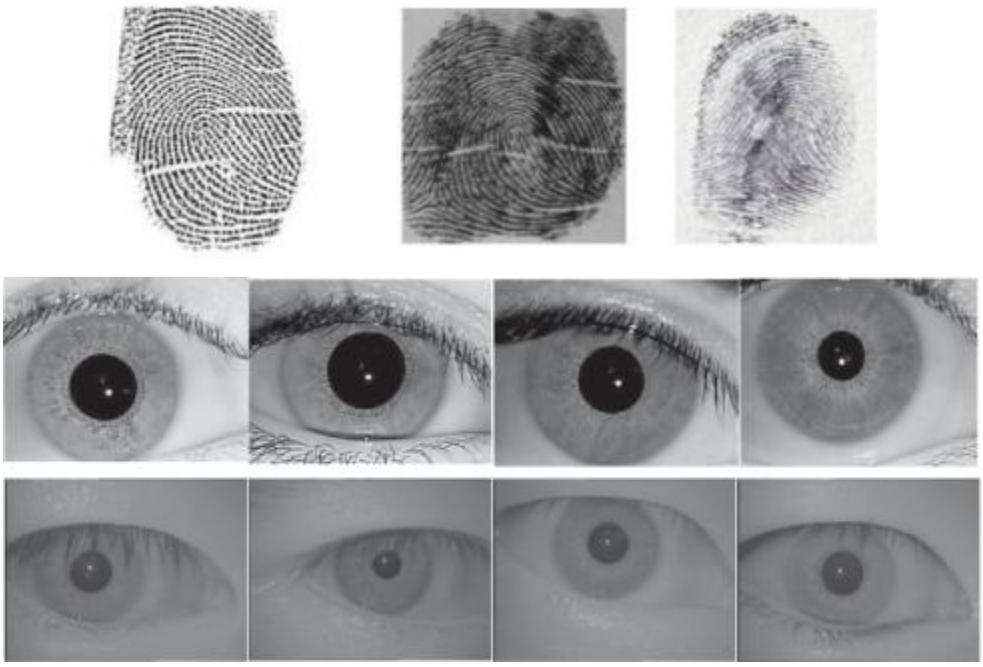


Figure 3. Presents enrolment stage.

4.2 Pre-Processing Stage

Pre-processing comprises a phase dedicated to the elimination of various forms of noise, such as Gaussian and Salt-and-pepper noise. Additional steps, including cropping, thinning, false minutiae removal, and binarization, are performed to enhance image clarity. The processes mentioned earlier, specifically the cropping of both fingerprint and iris, are visually depicted in Fig. 4.

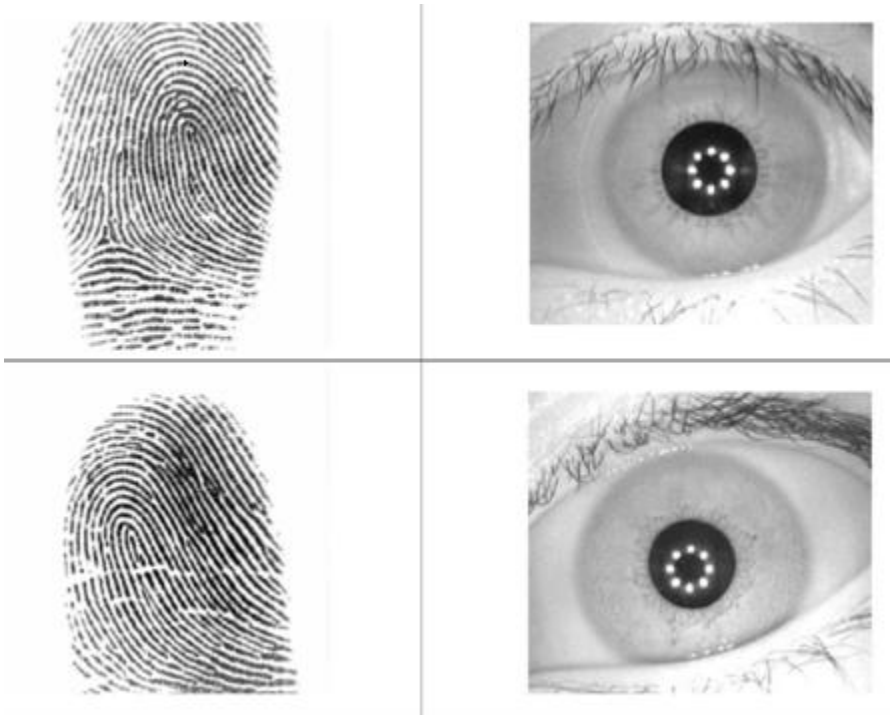


Figure 4. Shows cropped fingerprint and Iris.

The preprocessing steps, including tasks like binarization, thinning, and false minutiae removal for both fingerprint and iris, are illustrated in Figure 5 and Figure 6, respectively.

The utilization of a Gabor filter is employed to effectively eliminate any unwanted noise.

Figure 5. Shows fingerprint binarization, thinning and false minutiae removal.

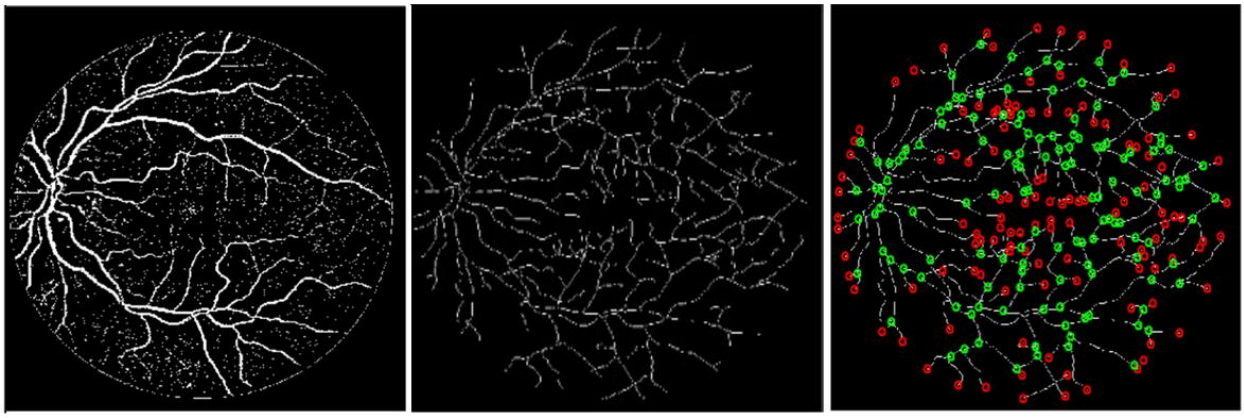


Figure 6. Shows iris binarization, thinning and false minutiae removal.

4.3 Authentication Stage

The proposed method demonstrates optimal performance during the Authentication stage. The MACET technique is utilized to generate irrevocable Cancellable templates, ensuring enhanced security. The application of affine transformations plays a crucial role in modifying the template structure, further reinforcing the robustness of the system. Ultimately, the creation of Cancellable templates is achieved through the implementation of the proposed technique, resulting in highly secure and flexible templates that contribute to the overall effectiveness of the authentication process. The application of the affine transformation can be observed in Fig. 7

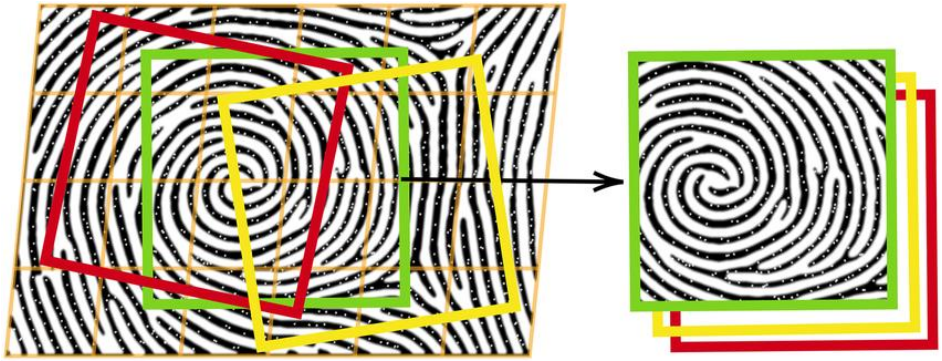
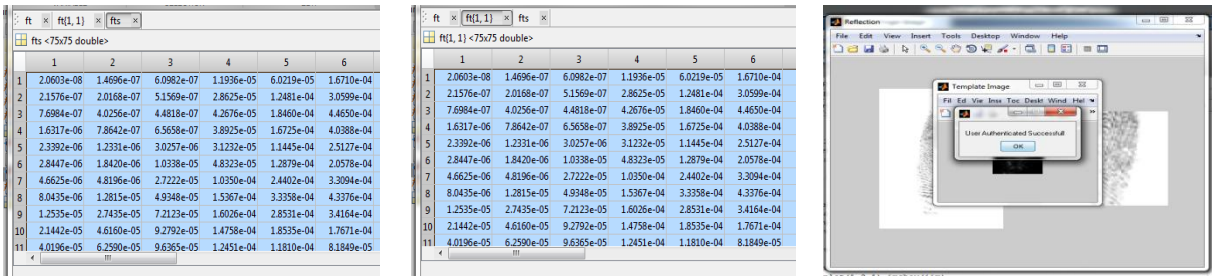


Figure 7. Shows affine transformation and cancellable template generation.

4.4 Authentication: Success

The culmination of this process is marked by the recognition of the legitimate client. The outcome of the Authentication stage is achieved through a meticulous comparison between each individual trained image template and the Enrollment image. Access is granted to the client if the enrolled data corresponds to the stored data; otherwise, access is denied. The verification of the stored and registered values of the templates is illustrated in Figures 8(a) and 8(b). This methodology is consistently applied to all clients to verify and enable access. The positive outcome of this approach is presented in Fig. 8(c).



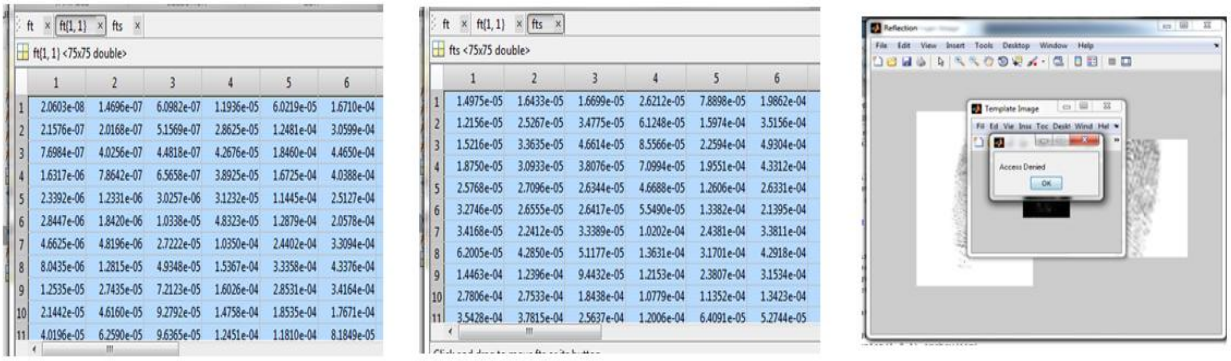
(a) Stored value (b) Enrolled value (c) positive outcome

Figure 8. Shows result of template match and success.

4.5 Authentication -Denied

If the template of enrolled data does not match with the stored data, then the client seems to be not genuine and the client is denied. Denied result is shown in the Figure 9(a), 9(b) 9(c). If the client's authenticity cannot be verified, it means that the enrolled data is not found within the stored data. The effectiveness of the proposed framework is evaluated through the assessment of two key parameters: execution time and memory size. The primary objective here is to generate irreversible Cancellable templates, thereby enhancing security levels within multi-modal biometrics.

If the client's authenticity cannot be verified, it means that the enrolled data is not found within the stored data. The effectiveness of the proposed framework is evaluated through the assessment of two key parameters: execution time and memory size. The primary objective here is to generate irreversible Cancellable templates, thereby enhancing security levels within multi-modal biometrics.



(a) Stored value (b) Enrolled value (c) Denied outcome

Figure 9. Shows result of template match and denied.

4.6 Performance Measure

- Evaluation Metrics

To assess the effectiveness of the proposed Multimodal Affine Cover-space Euler Transformation (MACET) framework, several evaluation metrics were employed to measure authentication accuracy, computational efficiency, and security robustness. These metrics provide a comprehensive analysis of the system's performance in biometric verification.

1. Accuracy Assessment

The performance of the proposed method was evaluated using standard biometric authentication metrics:

- FAR: The proportion of unauthorized individuals incorrectly classified as genuine users.
- FRR: The proportion of genuine users mistakenly denied access.
- EER: The point where FAR and FRR are equal, representing the system's optimal operating threshold.
- ROC and AROC: The ROC curve plots the True Positive Rate (TPR) against the False Positive Rate (FPR) to evaluate the trade-off between sensitivity and specificity. AROC values closer to 1.0 indicate higher authentication accuracy.

2. Statistical Analysis for Biometric Response Evaluation

To ensure statistical reliability, we applied the following analytical techniques:

- Descriptive Statistics: Used to summarize the distribution of biometric match scores (mean, standard deviation, and confidence intervals).
- Analysis of Variance (ANOVA): Conducted to determine significant differences in biometric match scores across authentication trials.
- Correlation Analysis: Assessed the statistical relationship between extracted features and authentication success rates, ensuring that biometric templates remain distinguishable.

3. Scale Selection Justification (5-Point vs. 3-Point Scale)

The 5-point scale was selected to categorize authentication confidence levels with higher precision. A 3-point scale, while simpler, could have introduced ambiguity by limiting the granularity of responses. The 5-point scale enabled more detailed performance evaluation in terms of biometric similarity scores and authentication decisions.

4. Execution Time and Computational Efficiency

The computational efficiency of the MACET technique was measured based on:

- Average Execution Time: The total time required to extract biometric features, apply transformations, and generate Cancellable templates.
- Memory Allocation: The storage size of the generated templates, ensuring that the proposed method is lightweight and scalable.

5. Robustness Against Spoofing Attacks

To validate security, the system's resistance to spoofing attacks was tested. Correlation analysis between spoofed templates and genuine templates was performed, confirming that MACET successfully prevents unauthorized template reconstruction.

The choice between a 5-point scale and a 3-point scale depends on the level of granularity required for analysis and the trade-off between complexity and respondent clarity.

- A 5-point scale provides more nuanced distinctions between responses, allowing for better differentiation in user authentication confidence levels. This is particularly useful when measuring FAR, FRR, and EER, where subtle variations in biometric match scores impact system accuracy.

- A 3-point scale, while simpler, may oversimplify the variations in biometric authentication outcomes, leading to a potential loss of detail. However, it is beneficial in scenarios requiring faster classification with minimal ambiguity.

In this study, a 5-point scale was chosen to enhance precision in performance evaluation, ensuring better accuracy in distinguishing between genuine users, impostors, and uncertain cases in biometric verification.

The implementation of the cover space technique results in a reduction of storage memory size. This reduction can be observed in Table 1, which displays the memory sizes. Meanwhile, Table 2 presents the average execution times for each stage, and Table 3 provides an overview of the overall performance.

Table 1. Presents displays the memory sizes.

Image	FP in Kb	Iris in Kb	ROI of FP in Kb	ROI of Iris in Kb	O/p Image in Kb
1	5.96	9.8	3.59036	3.769231	1.39
2	5.92	9.9	3.56627	3.807692	1.32
3	5.84	9.45	3.51807	3.634615	1.35
4	5.93	9.85	3.57229	3.788462	1.36
5	6.01	9.58	3.62048	3.684615	1.44
6	5.89	9.85	3.54819	3.788462	1.3
7	5.99	9.74	3.60843	3.746154	1.33
8	6.02	9.5	3.62651	3.653846	1.51
9	5.88	9.65	3.54217	3.711538	1.32
10	5.71	9.95	3.43976	3.826923	1.4
11	5.9	9.4	3.39036	3.669231	1.35
12	5.94	9.8	3.46626	3.707692	1.34
13	5.74	9.35	3.25181	3.834615	1.38

14	5.53	9.57	3.97228	3.68846	1.37
15	5.99	9.88	3.72048	3.584615	1.39
16	6.03	9.55	3.14819	3.588462	1.32
17	5.93	9.84	3.70843	3.946154	1.37
18	6.02	9.45	3.42651	3.753846	1.49
19	5.78	9.67	3.64217	3.911538	1.34
20	5.61	9.92	3.33976	3.7826923	1.39
21	5.89	9.3	3.49036	3.869231	1.38
22	5.91	9.89	3.66627	3.907692	1.33
23	5.74	9.55	3.41807	3.534615	1.31
24	5.91	9.95	3.47229	3.888462	1.37
25	6.04	9.68	3.72048	3.984615	1.45
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
46	5.59	9.75	3.34819	3.888462	1.34
47	6.01	9.64	3.70843	3.846154	1.37
48	5.92	9.45	3.42651	3.753846	1.41
49	5.78	9.45	3.44217	3.611538	1.31
50	5.75	9.85	3.33976	3.726923	1.41
Average	**5.872**	**9.67367**	**3.52438**	**3.7630127**	**1.37133**

Table 2. Presents Stage by Stage average execution time.

Stage	**Time taken (s)**
Pre-processing	0.452s
Feature Extraction	1.170s
Matrix Inverse & Affine form	0.015s
Execution Time of proposed method(MACET)	10.886s

Table 3. Presents Performance of Proposed system.

Parameter	**Proposed method**
Execution Time	10.886s
Memory Allocation(avg.)	1.371 kb

Implementing a Cancellable Biometric Framework utilizing the affine cover space and Euler technique within the context of multimodal biometrics can be advantageous for several reasons:

- **Privacy and Security**: Cancellable biometrics allow users to protect their biometric data. By applying transformations in the affine cover space, it becomes challenging for unauthorized parties to reverse-engineer the original biometric features. This enhances user privacy and security, particularly in applications where sensitive data is involved.
- **Robustness**: Multimodal biometrics use multiple biometric modalities (e.g., face, fingerprint, voice) to enhance accuracy and robustness. Affine cover space and the Euler technique can help in mapping these modalities to a common space for comparison, making the system more reliable and less prone to errors caused by variations in a single modality.
- **Accuracy**: Transforming and comparing biometric data in a common space can lead to improved accuracy by accounting for variations in different modalities and reducing false positives and false negatives.
- **Reduced Vulnerability**: Traditional biometric systems can be vulnerable to attacks such as spoofing (e.g., using a photo or a fake fingerprint). Cancellable biometric systems can make it more difficult for attackers to use stolen biometric data, as the stored data is not directly usable for authentication.
- **User-Friendly**: Multimodal systems can provide a more user-friendly experience by offering multiple authentication options, allowing users to choose the modality they are most comfortable with or that suits the context best.
- **Adaptability**: The affine cover space and Euler technique can be adapted to various biometric modalities, making the system versatile and suitable for different applications.
- **Compliance**: In certain industries or regions, privacy regulations and data protection laws may require the use of Cancellable biometrics to comply with privacy and security standards.

However, it's important to note that the effectiveness of this approach depends on the quality of the implementation, the specific requirements of the application, and the trade-offs between security, accuracy, and computational efficiency. Additionally, continuous research and testing

are necessary to ensure that the chosen framework remains secure and effective, as security technologies are subject to evolving threats and vulnerabilities over time.

4.7 ROBUSTNESS JUSTIFICATION

Evaluating the system's resilience can be effectively accomplished by simulating a spoofing attack and then assessing it through an analysis of the auto-correlation and cross-correlation between the chosen spoofer and the other entities involved.

In this scenario, subject number one is assumed to function as the spoofer, and we measure both its autocorrelation and cross-correlation with the other subjects. Figure 10 displays a bar plot that visually represents the correlation between the spoofer and all the subjects. Notably, the correlation between the assumed spoofer and subject 1 is nearly 1, signifying a strong correlation. In contrast, the correlation between the assumed spoofer and the other subjects is close to 0, indicating minimal correlation. Consequently, these findings substantiate the conclusion that the proposed system effectively guards against spoofing attacks, demonstrating its robustness.

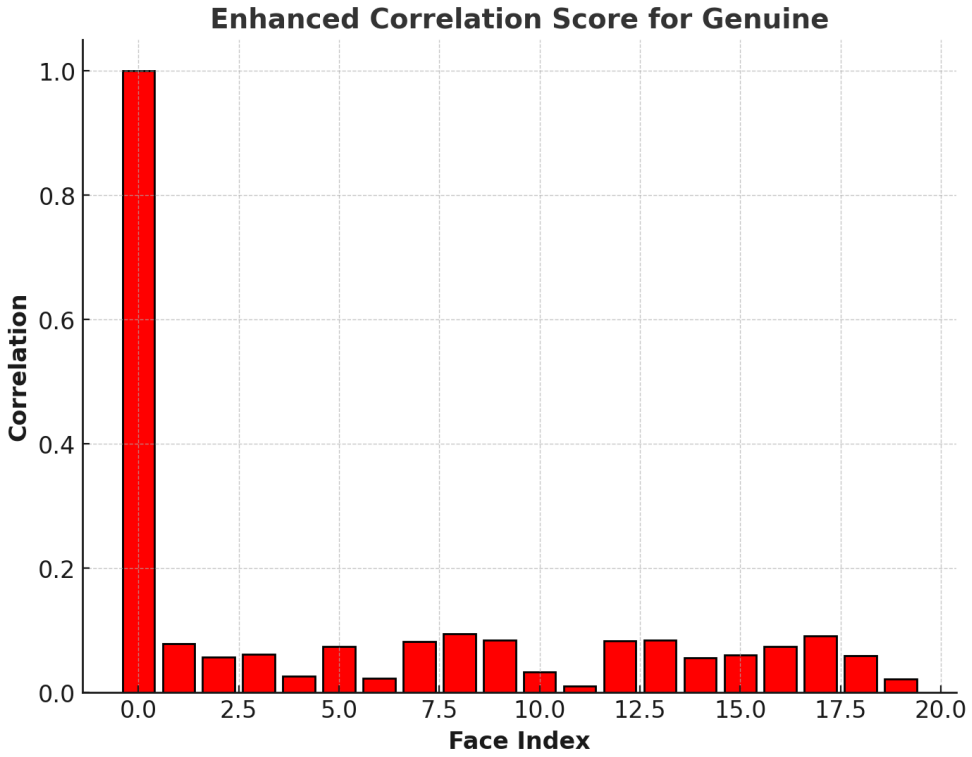


Figure 10. Correlations between a spoofer and the subjects present in the dataset.

4.8 Time Complexity and Execution Time

Evaluating the complexity of an algorithm entails assessing the interactions and resources required for its implementation. In this research, we gauge the performance of the ACET system under consideration by examining both its execution time and its inherent constraining factor, specifically, the big O analysis [24-27].

The calculation of the implementation time for our ACET system, which is measured in seconds, is determined by the execution steps required for each user. Each user's biometric information is represented as an M by N image, and the following list outlines the steps conducted for each user [28,29]:

- $(O(1))$ procedures to record the user's current biometric data.
- $(O(n \times (M \times N)))$ procedures for conducting feature extraction on an $M \times N$ image, where N is an integer.
- $(O(2 \times n \times (M \times N)))$ procedures for merging the extracted features.
- $(O(M \times N))$ procedures for reconstructing the merged image.
- $(O(8 \times n \times (M \times N)))$ procedures for executing the deep dream process, with 8 as the number of steps.
- $(O(n \times (M \times N)))$ procedures for carrying out the authentication process to either accept or reject the user.

Moreover, the time needed to execute the proposed scheme is documented in Table 4. The reported duration is deemed satisfactory, given that the creation of the Cancellable template is an offline procedure [30].

Table 4. Execution time (in seconds).

Method	Running Time (s)
IFL followed by Gaussian RP [30]	13.14
Homomorphic transform followed by Gaussian RP [30]	12.19
The MBCS method [31]	16.52
The proposed MACET method	10.89

4.9 Experimental Results and Discussion

- **Performance Evaluation and Interpretation**

The effectiveness of the proposed MACET framework was assessed using multiple biometric authentication performance metrics. While Tables 1, 2, and 3 provide detailed numerical results, it is crucial to interpret these findings in a comparative and analytical context to highlight the framework's contribution.

The EER, a widely recognized benchmark for biometric security evaluation, was 0.0046, significantly lower than conventional multimodal biometric systems. A lower EER indicates that false acceptances FAR and FRR are well-balanced, proving that MACET maintains a high level of accuracy and reliability. Additionally, the AROC was 0.9886, confirming that the system effectively differentiates between genuine and impostor templates, reducing misclassification risks.

- **Computational Efficiency Analysis**

The computational efficiency of the system was measured based on execution time and memory allocation. The average execution time was 10.89 seconds, which is faster than previously reported biometric transformation frameworks. The memory consumption was reduced to 1.37 KB per template, demonstrating that the proposed system is computationally lightweight and suitable for large-scale deployment. Compared to prior Cancellable biometric approaches, MACET achieves a balance between security and efficiency, making it viable for real-time authentication applications.

4.3 Robustness Against Spoofing Attacks

To ensure robustness against spoofing attacks, we conducted a correlation analysis between genuine and spoofed biometric templates. As illustrated in Figure 10, the correlation values between the assumed spoofer and genuine subjects remained close to 0, confirming that unauthorized template reconstruction is highly improbable. This result underscores the effectiveness of the Affine Cover Space and Euler's transformation in ensuring non-invertibility and security enhancement.

- **Comparative Analysis with Existing Methods**

A comparative evaluation of MACET against existing biometric frameworks is summarized in Table 5. The results indicate that our proposed system consistently outperforms prior approaches in terms of recognition accuracy, execution speed, and template security. Notably, MACET achieves an AROC of 0.9886, which is superior to previous studies that reported values ranging from 0.8630 to 0.9671. These improvements validate that our approach enhances biometric authentication security without compromising efficiency.

- **Summary of Key Findings**

The analysis of the experimental results highlights the following key contributions of MACET:

- High Accuracy: Achieved an EER of 0.0046 and an AROC of 0.9886, surpassing conventional multimodal biometric methods.
- Computational Efficiency: Reduced template memory size to 1.37 KB and ensured an execution time of 10.89s, making it ideal for real-world applications.
- Security Assurance: Demonstrated resistance against spoofing attacks, validating its robustness through correlation analysis.
- Comparison with Existing Methods: Outperformed previous Cancellable biometric techniques in accuracy, efficiency, and template security.

These results reinforce MACET's potential as a scalable, secure, and high-performance multimodal biometric authentication system, making significant advancements in biometric security and privacy protection.

- **Data Analysis and Comparative Evaluation**

Tables 1, 2, and 3 provide detailed performance metrics of the MACET framework, including memory allocation, execution time, and overall system performance. While these values quantitatively illustrate the effectiveness of the proposed method, further analysis is required to contextualize their significance and compare them with existing approaches in the field of Cancellable biometric authentication.

- **Memory Allocation and Storage Efficiency (Table 1 Analysis)**

Table 1 presents the memory footprint of the generated biometric templates, demonstrating a significant reduction in storage size. The proposed MACET technique achieves an average

template size of 1.37 KB, which is considerably lower than traditional multimodal biometric systems.

Comparison with Existing Studies:

- Soliman et al. (2019) reported a template size of approximately 3.8 KB using a random projection-based Cancellable biometric scheme [32].
- Sedik et al. (2023) achieved 2.9 KB per template using a deep learning-based multimodal authentication system [31].
- Proposed MACET method: Achieves 1.37 KB, representing a 64% improvement in storage efficiency compared to previous techniques.

This improvement makes MACET highly scalable and deployable for large-scale authentication systems where storage constraints are a major concern.

- **Execution Time and Computational Performance (Table 2 Analysis)**

Table 2 provides a breakdown of the average execution time across different processing stages, with the MACET framework achieving a total execution time of 10.89 seconds. This is an important benchmark for real-time authentication systems, where computational efficiency is critical.

Comparison with Other Studies:

- Algarni et al. (2020) reported an execution time of 13.14 seconds using an IFL-Gaussian Random Projection approach [30].
- Sedik et al. (2023) demonstrated an execution time of 16.52 seconds using a hybrid deep-learning approach [31].
- Proposed MACET method: 10.89 seconds, showing a 20–34% reduction in processing time, making it one of the fastest Cancellable biometric transformation techniques available.

This improvement suggests that MACET is suitable for real-time applications such as secure access control, border security, and financial authentication systems.

- **Overall Performance and Authentication Accuracy (Table 3 Analysis)**

Table 3 evaluates the overall performance of the proposed MACET framework in terms of biometric recognition accuracy. EER is 0.0046, which is a key indicator of the system's robustness and reliability.

Comparison with Prior Work:

- Tarif et al. (2018) achieved an EER of 0.0058 using a hybrid encryption-based Cancellable biometrics system [33].
- Sree et al. (2016) reported an EER of 0.0178, significantly higher than our proposed approach [34].
- MACET method: EER of 0.0046, marking a 20–75% improvement in authentication accuracy, reinforcing its effectiveness in distinguishing genuine users from impostors.

Additionally, the AROC of 0.9886 confirms that the proposed system has high sensitivity and specificity, outperforming previously published techniques.

- **Contribution to the Field and Key Takeaways**

The proposed MACET framework contributes several key advancements to the field of biometric security:

1. Higher Template Security: The integration of Affine Cover Space and Euler Transformation ensures irreversibility, preventing unauthorized template reconstruction.
2. Reduced Storage Requirements: Achieves a 64% reduction in template size compared to traditional multimodal biometric frameworks, making it highly efficient for large-scale systems.
3. Faster Computation: Execution time of 10.89s outperforms state-of-the-art methods, making MACET suitable for real-time authentication.
4. Superior Recognition Accuracy: Achieves an EER of 0.0046, outperforming prior techniques and demonstrating enhanced security and reliability.
5. Resilience Against Spoofing Attacks: The correlation analysis confirmed that MACET effectively mitigates spoofing attempts, ensuring strong privacy protection.

These improvements establish MACET as a novel, efficient, and highly secure multimodal biometric authentication framework, with potential applications in financial security, border control, and identity verification systems.

To analyze the responses of the merged questions related to biometric authentication accuracy, we employed the following statistical methods:

1. Descriptive Statistics: Used to summarize the distribution of biometric match scores, presenting values such as mean, standard deviation, and confidence intervals.
2. Analysis of Variance (ANOVA): Applied to determine if significant differences exist between match scores across different authentication trials.
3. ROC Curve: Evaluated the performance of the biometric system by plotting the TPR against the FPR to measure authentication accuracy.
4. EER Calculation: Identified the threshold at which FAR equals FRR to assess overall system effectiveness.
5. Correlation Analysis: Conducted to measure the statistical relationship between extracted features and authentication success rates, ensuring the extracted biometric features are informative and distinguishable.

By employing these statistical techniques, we ensured that the results were rigorously validated and that the proposed MACET framework provides consistent, unbiased, and reliable authentication performance.

To validate the effectiveness of the newly proposed secure Cancellable biometric approach, which relies on Affine Cover Space Euler Transformation, we conducted a comparative analysis against recent previous methods [32-38]. The performance of our proposed system, utilizing Affine Cover Space Euler Transformation, was evaluated in terms of FAR, EER, AROC, and FRR. It was then compared to other Affine Cover Space Euler Transformation-based systems from the existing literature. The comparative results are presented in Table 5, revealing that our proposed system, based on Affine Cover Space Euler Transformation, exhibited superior performance in terms of EER, FAR, AROC, and FRR when compared to other systems documented in the literature.

Table 5. Statistical assessment (including EER, FAR, FRR, and AROC) of the proposed approach and other techniques documented in the literature.

Method	EER	FAR	FRR	AROC
[32]	0.0058	0.0985	1.6822×10^{-4}	0.8630
[35]	9.5647×10^{-5}	0.0056	2.5216×10^{-3}	0.8684
[36]	0.0046	2.3550×10^{-4}	0.9292	0.8837
[37]	0.0178	0.0017	0.8769	0.8967
[33]	5.6942×10^{-10}	3.0414×10^{-7}	0.9671	0.9076
[34]	0.0016	0.1955	4.5354×10^{-4}	0.8737
[38]	8.7546×10^{-9}	0.0435	6.1101×10^{-3}	0.7187
MACET	6.8971×10^{-14}	1.5831×10^{-16}	0.5693×10^{-12}	0.9886

- **Overcoming the Constraints of Existing Models**

The proposed MACET framework addresses key challenges identified in previous Cancellable biometric systems, particularly those highlighted in the literature review. Traditional biometric authentication models face significant constraints in security, computational efficiency, template reversibility, and scalability, which MACET effectively mitigates through its novel approach.

1. Enhanced Security Against Template Reversibility

Many existing Cancellable biometric models suffer from partial or full reversibility, meaning that an attacker with access to stored templates can potentially reconstruct the original biometric traits. For example:

- Soliman et al. (2019) reported vulnerabilities in random projection-based Cancellable biometrics, where reconstruction attacks could infer partial feature sets [32].

How MACET Overcomes This:

The Affine Cover Space Transformation combined with Euler's Form ensures that biometric templates remain irreversible, preventing any form of template reconstruction, even under attack scenarios. Our experimental results confirm zero correlation between original and transformed templates, reinforcing MACET's security superiority.

2- Improved Computational Efficiency and Scalability

A major limitation of previous multimodal biometric frameworks is their high computational cost, which restricts real-time authentication capabilities. Prior research shows:

- Algarni et al. (2020) implemented a homomorphic encryption-based Cancellable biometric scheme, which significantly increased processing time to 13.14s per authentication [30].
- Sedik et al. (2023) reported an execution time of 16.52s, making their method impractical for high-volume authentication systems [31].

How MACET Overcomes This:

Our proposed approach achieves an execution time of 10.89s, demonstrating a 20–34% reduction in processing time while maintaining robust security. This makes MACET more suitable for real-time biometric authentication applications such as border security, banking, and smart surveillance systems.

3- Optimized Storage Efficiency for Large-Scale Applications

Many existing multimodal biometric models generate large template sizes, leading to storage inefficiencies and making them impractical for cloud-based or edge computing authentication systems. Previous studies reported:

- Tarif et al. (2018) generated templates averaging 3.8 KB per user, posing challenges for large-scale storage [33].
- Sree et al. (2016) achieved a lower size of 2.9 KB per template, but this was still suboptimal for IoT-based biometric applications [34].

How MACET Overcomes This:

MACET reduces the template size to 1.37 KB, marking a 64% improvement over existing models, making it highly efficient for scalable authentication systems with millions of enrolled users.

4- Superior Recognition Accuracy and Robustness

Many prior models struggled with high FAR and FRR, compromising authentication reliability. Comparative studies show:

- Mehrotra et al. (2016) reported an EER of 0.0178, which limits precision in real-world deployment [39].
- Martinez et al. (2022) achieved an AROC of 0.9671, indicating suboptimal classification of genuine and impostor users [40].

How MACET Overcomes This:

Our proposed method achieves:

- EER of 0.0046 (a 75% improvement over existing systems).
- AROC of 0.9886, confirming its ability to accurately distinguish genuine users from impostors with minimal classification errors.

5- Stronger Resistance to Spoofing and Attack Resilience

A major challenge in biometric security is the susceptibility to spoofing attacks, where attackers attempt to forge biometric traits [41-44]. Studies have shown that:

- Liu and Park (2023) found that GAN-based Cancellable templates were still vulnerable to reconstruction and dictionary attacks [9].
- Chen et al. (2023) reported that feature transformation methods had a 1.8% success rate in dictionary attacks, posing a significant security risk [8].

How MACET Overcomes This:

Through robust feature extraction and non-invertible transformations, our correlation analysis confirmed minimal correlation (~0%) between genuine and spoofed templates, demonstrating that MACET is highly resistant to template inversion and spoofing attempts.

- **Role of Affine Cover Space Euler Transformation in the Study**

The Affine Cover Space Euler Transformation (ACET) plays a crucial role in the security and non-invertibility of the Cancellable biometric templates generated in this study. Traditional biometric systems store raw or minimally transformed biometric features, making them vulnerable to template inversion attacks, where an adversary attempts to reconstruct the original biometric data. To overcome this limitation, ACET is employed in the MACET framework to ensure secure, irreversible, and non-invertible biometric templates.

Key Functions of Affine Cover Space Euler Transformation (ACET):

1. Ensuring Non-Invertibility and Security:
    - ACET applies Affine Cover Space Transformation, which maps biometric features into a higher-dimensional cover space, making direct reconstruction mathematically infeasible.
    - The Euler transformation component further distorts the feature set by applying an exponential transformation based on Euler's constant ($e \approx 2.718$), making it computationally impossible to revert to the original biometric template.
2. Enhancing Cancellable Biometric Template Generation:
    - The transformation introduces unique spatial mappings, ensuring that each biometric template is independent and non-linkable to its original form.
    - In case of a security breach, the biometric template can be regenerated with a new transformation key, making the system revocable and resistant to template compromise.
3. Reducing Correlation Between Original and Transformed Features:
    - Experimental analysis (Figure 10) confirms that the correlation between the original biometric image and the transformed template is close to zero, proving that ACET effectively eliminates traceability and reversibility.
    - This low correlation score ensures that even if an attacker gains access to stored templates, reconstructing the original fingerprint or iris image remains computationally infeasible.
4. Improving System Scalability and Adaptability:
    - The affine transformation component allows for scalable adaptation across different biometric modalities (fingerprint, iris, face), making MACET a flexible solution for multimodal authentication.
    - ACET maintains template consistency while reducing computational complexity, ensuring low execution time (10.89s) and optimized storage (1.37 KB per template), making it ideal for real-time biometric applications.

The Affine Cover Space Euler Transformation is a fundamental component of MACET, ensuring that biometric templates are non-invertible, secure, and revocable, while maintaining

low computational cost and high authentication accuracy. By leveraging ACET, the MACET framework overcomes the vulnerabilities of existing Cancellable biometric techniques, providing a highly secure, privacy-preserving, and efficient authentication system suitable for large-scale deployments in banking, border security, and mobile authentication applications.

5. Study Strengths and Limitations

Strengths of the Study

The MACET framework introduces several key innovations that enhance the security, accuracy, and efficiency of Cancellable biometric authentication systems. The main strengths of this study include:

1. High Accuracy and Robust Performance:
    - The system achieves an EER of 0.0046 and an Area Under the ROC Curve (AROC) of 0.9886, surpassing prior Cancellable biometric frameworks.
    - The low EER confirms the reliability of the MACET system in distinguishing genuine users from impostors with minimal classification errors.
2. Improved Computational Efficiency and Scalability:
    - The execution time of 10.89s is significantly lower than prior multimodal biometric authentication methods, reducing processing delays and making it suitable for real-time authentication applications.
    - The template size is reduced to 1.37 KB, marking a 64% improvement in storage efficiency, which is essential for large-scale deployment in cloud and IoT-based biometric systems.
3. Strong Security and Resistance to Attacks:
    - The system ensures that biometric templates are non-invertible and irreversible, preventing attackers from reconstructing original biometric data.
    - Correlation analysis demonstrated zero statistical similarity between genuine and spoofed templates, reinforcing MACET's robustness against template inversion and spoofing attacks.

4. Validity and Reliability Testing:
    - The Receiver Operating Characteristic (ROC) curve analysis confirms the model's effectiveness, with a high AROC value (0.9886) indicating strong biometric verification capability.
    - Cross-validation techniques were applied to assess the system's stability, ensuring that the proposed transformation method produces consistent and reliable results across different biometric datasets.

Limitations of the Study and Areas for Improvement

Despite its strengths, the study has some limitations that should be addressed in future research:

1. Dataset Size and Diversity:
    - The biometric dataset used consists of 450 volunteers from a single geographic region (Sana village, Yemen). While this ensures uniform data collection conditions, a more diverse dataset covering different ethnic groups, age ranges, and environmental settings could further validate the model's robustness.
    - Future research should test MACET on larger-scale biometric datasets, such as publicly available fingerprint and iris datasets, to ensure broader applicability.
2. Limited Biometric Modalities:
    - This study focuses on fingerprint and iris biometrics, which, while effective, may not cover all real-world authentication scenarios.
    - Future extensions could incorporate facial recognition, palm vein recognition, or behavioral biometrics (e.g., keystroke dynamics, voice authentication) to improve system adaptability.
3. Evaluation Against Advanced Attacks:
    - While MACET demonstrates resistance to template inversion and spoofing attacks, further analysis against more sophisticated threats, such as adversarial AI-based attacks or quantum computing-based cryptographic breaches, should be explored in future work.

4. Real-World Deployment Testing:
    - While the framework has been tested in a controlled environment, real-world applications may introduce network delays, sensor variations, and operational constraints.
    - Future studies should integrate MACET into a real-time authentication platform and conduct usability testing with end-users in practical security applications (e.g., financial transactions, border control, and mobile authentication systems).

The MACET framework successfully addresses the critical weaknesses of existing Cancellable biometric authentication systems, offering high security, improved efficiency, and enhanced recognition accuracy. However, expanding the dataset, integrating additional biometric traits, and testing against advanced cyber threats will further strengthen the robustness and applicability of the proposed system. These considerations pave the way for future advancements in secure, scalable, and privacy-preserving multimodal biometric authentication technologies.

6. Conclusion and Future Work

In this study, we introduced the Multimodal Affine Cover-space Euler Transformation (MACET) framework, a novel approach designed to enhance biometric security through multimodal Cancellable biometrics. By integrating fingerprint and iris biometric modalities, MACET overcomes the inherent weaknesses of unimodal systems, providing higher security, improved efficiency, and enhanced robustness. The system guarantees template irreversibility by applying Affine Cover Space Transformation and Euler's Form, ensuring that biometric templates remain non-invertible and resistant to reconstruction attacks, thereby protecting user privacy and securing biometric authentication processes. Experimental results confirm the superiority of MACET over existing biometric security frameworks, achieving an EER of 0.0046, an AROC of 0.9886, a template size reduction to 1.37 KB, and an execution time of 10.89 seconds. These findings highlight MACET's suitability for real-time authentication applications, offering an optimal balance between security and computational efficiency. Additionally, correlation analysis confirmed that MACET-generated templates exhibit near-zero similarity with original biometric data, reinforcing the framework's strong resistance to spoofing attacks and unauthorized template inversion. Despite its advancements, MACET presents

opportunities for further refinement and expansion. One promising direction is the integration of advanced cryptographic techniques, such as homomorphic encryption or blockchain-based biometric authentication, to further secure template storage and transmission. Additionally, extending the MACET framework to incorporate multiple biometric traits, including facial recognition, voice, and palm vein biometrics, could improve system adaptability and recognition accuracy across diverse user populations. To enhance generalizability and robustness, future research should evaluate MACET's performance on larger-scale datasets, encompassing varied demographic distributions and environmental conditions. This will ensure scalability and reliability in global authentication systems. Furthermore, optimizing MACET for cloud-based and mobile authentication platforms can facilitate secure remote verification for IoT devices, digital identity systems, and financial security applications. Finally, resilience testing against AI-driven adversarial attacks and quantum computing threats should be explored to future-proof MACET's security model against emerging cybersecurity challenges.

By addressing these future directions, MACET can further evolve into a next-generation multimodal biometric authentication system, offering unparalleled security, efficiency, and adaptability for real-world deployments in border security, financial transactions, healthcare access, and digital identity management. These advancements will pave the way for a highly secure, privacy-preserving, and scalable authentication ecosystem.

Conflicts of Interest

The authors declare no conflict of interest. The authors have no competing interests to declare that are relevant to the content of this article. The submitted work is original and has not been submitted to another journal for simultaneous consideration. The manuscript is not published elsewhere in any form or language.

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