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Original Article

Biometric Authentication for Secure Digital Banking

Dr. Ali Reza[1], Dr. Maria Gonzalez[2]

[1]*Professor, University of Tehran, Iran.*

[2]*Associate Professor, University of Barcelona, Spain.*

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ABSTRACT

Digital banking has revolutionized financial services by enabling convenient online transactions, account management, investments, and payments. However, it has also increased security risks such as identity theft, phishing, credential compromise, and unauthorized access. Traditional authentication methods, including passwords and PINs, are vulnerable to cyberattacks, leading financial institutions to adopt biometric authentication technologies. Biometric authentication uses unique physiological and behavioral traits such as fingerprints, facial recognition, iris patterns, voice recognition, and behavioral biometrics to verify user identities. Enhanced by Artificial Intelligence (AI), Machine Learning (ML), and computer vision, modern biometric systems offer improved accuracy, security, and user convenience. This study analyzes biometric authentication mechanisms in digital banking, comparing various biometric modalities based on authentication accuracy, security, usability, and implementation complexity. It also examines multimodal biometric systems that combine multiple biometric traits to enhance reliability and prevent spoofing attacks. A secure biometric framework is proposed, integrating fingerprint recognition, facial verification, liveness detection, encrypted biometric templates, and multi-factor authentication. Experimental results show that biometric authentication provides higher security, lower error rates, and a better user experience than traditional methods. The findings highlight biometric authentication as a key technology for securing digital banking systems. Future advancements in AI, blockchain, and privacy-preserving biometrics are expected to further strengthen authentication mechanisms and support the development of secure, scalable, and user-friendly financial services.

KEYWORDS

Biometric Authentication, Digital Banking, Cybersecurity, Fingerprint Recognition, Facial Recognition, Multi-Factor Authentication, Machine Learning, Identity Verification, Financial Security, Liveness Detection.

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1. INTRODUCTION

1.1. Background of Digital Banking

In the last 10 years, the banking sector has undergone a tremendous change with the advent of information and communication technologies. Digital banking has grown to become a convenient and efficient way to provide financial services, giving customers access to banking facilities via mobile apps, internet banking portals, automated teller machines (ATMs) and other smart devices, without having to visit physical banks. This technological advancement has boosted the efficiency of operations, cut transaction processing costs, expanded service accessibility, and lifted customer satisfaction. The proliferation of smartphones, internet connectivity and cloud-based technologies has made digital banking services grow at a faster rate across the world. Today, customers are able to undertake various financial activities without having to visit a branch, such as moving money between accounts, paying bills, updating accounts, investing, and applying for loans. But the digital banking explosion has also meant that there's been an uptick in threats like phishing, credential theft, malware, and unauthorized access. These attacks can be particularly devastating for traditional methods of authentication, such as passwords and PINs, which are often susceptible to these types of attacks, and has led to the necessity of more secure and reliable means of authentication that can protect users' identities and provide a smooth banking experience.

1.2. Need for Biometric Authentication

Biometric authentication is now proving to be a viable and secure solution to the security issues that traditional authentication methods like passwords, pin codes and security questions incur. Biometric attributes are unique to each person, and are much harder to duplicate or fake than knowledge-based credentials. With the growing complexity of cyber threats, financial institutions are turning to biometric technologies as a way to enhance their identity verification procedures, while keeping users happy and comfortable. Today's authentication methods encompass a range of biometric modalities, each with its own unique strengths and weaknesses in security, accuracy, and user-friendliness.

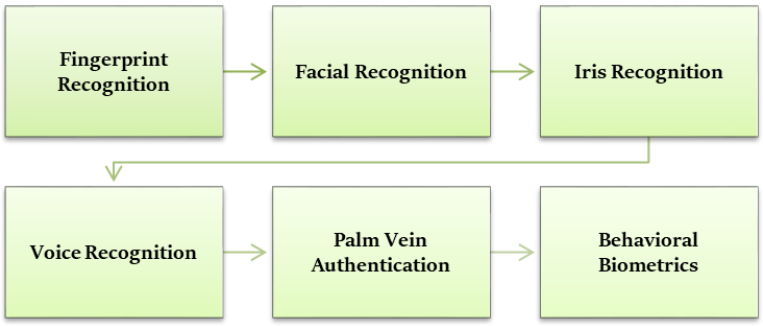

Fig 1 - Need for Biometric Authentication

1.2.1. Fingerprint Recognition

The use of fingerprint recognition is one of the most popular biometric authentications because it is cheap, easy to implement and very accurate. Recognizes individuals based on the ridge

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PP: 01-16.

patterns, ridge endings and bifurcation points on their fingertips. Fingerprints are unique to each person, so this is a reliable identity verification modality. Fingerprint authentication is widely used in mobile phones, ATMs, and banking apps due to its speed and convenience, along with its security.

1.2.2. Facial Recognition

Facial recognition verifies the users based on unique facial features like eyes, nose, mouth, facial contours, and geometric relationships between the facial landmarks. The improvement of AI technology and AI deep learning has significantly enhanced the accuracy of facial recognition systems and made it possible for use in digital banking applications. This contactless authentication solution provides an unparalleled user experience, making identification easy with just a quick glance at a camera, which is convenient for customers.

1.2.3. Iris Recognition

Iris recognition involves the identification of persons by the unique structure of the coloured area around the eye's pupil. These patterns are stable and do not change during a person's life, and are very hard to duplicate, making iris recognition one of the most secure biometric modalities. The technology is extremely accurate and effective against spoofing attacks, ideal for high-security banking systems where authentication is a critical factor.

1.2.4. Voice Recognition

Voice recognition is a method that compares the voice characteristics such as tone, pitch, frequency, pronunciation patterns and features of the vocal tract of a person's voice in order to confirm identity. This biometric modality offers a hands-free, remote authentication solution which is great for telephone banking, customer support systems and voice-based digital services. Voice authentication is not only a more convenient and accessible technology but also an added security measure for verification.

1.2.5. Palm Vein Authentication

Palm vein authentication is based on the identification of user based on the unique vein pattern that is found under the skin on the palm. These patterns are in the body and are impossible to mimic using infrared imaging technology. Due to the uniqueness and durability of the vein, palm vein authentication is highly resistant to spoofer attacks and identity theft. This technology is becoming more popular in applications such as high-security financial and healthcare applications.

1.2.6. Behavioral Biometrics

Behavioral biometrics verify the user using their behavior, not their physical attributes. Patterns can be typing rhythms, touch screen patterns, mouse movements and navigations, device handling patterns, or transaction patterns. Behavioral biometrics constantly track the user's behavior while using the system, allowing continuous authentication to take place instead of just at a single moment. This method helps to improve security by identifying suspicious activity that could signify that a user is accessing their account illegally or their account has been compromised and is a valuable addition to the security systems of modern-day digital banking.

ISSN: 3071-642X
PP: 01-16.

1.3. Challenges in Traditional Authentication

Many online services and banking systems have been traditionally secured for many years now using traditional authentication methods, which are mostly password-based and PIN-based, and in some cases even security question-based. But the surge of digital banking and the ever-evolving nature of the cyber-attack has revealed some serious flaws with these traditional methods of authentication. Vulnerability to passwords remains a prime problem area, and is a major factor in the compromising of accounts. A lot of people use simple passwords that are easy to guess or use personal details or common words. Additionally, users often use the same credentials for multiple sites and applications, which can make it more susceptible to being breached from one site to others. These practices render password based systems extremely vulnerable to brute force attacks, dictionary attacks, and credential-stuffing attacks. The proliferation of phishing attacks, which involves sending fake emails, SMS, phone calls or fake websites to trick users to give their login credentials, is also a significant security issue. Such attacks may appear to be authentic banking emails and messages can be very convincing, making it hard for users to tell if an email or message is genuine or not. If attackers succeed in getting the log-in information, they can access sensitive banking accounts and make fraudulent transactions. For instance, with large databases of different organizations around the world being breached, credential theft has become a common occurrence. Every year, millions of usernames and passwords are leaked due to cyber incidents, and these can be the basis for an attacker to gain access to banking systems and financial services. Even traditional authentication mechanisms are at risk from social engineering – a more psychological attack – because social engineering attacks work against technical flaws, relying on the psychology of the human being instead. Social engineering exploits people who willingly give up information because they think they are talking to a trusted source, because they feel they must act quickly or because they are not aware of cybersecurity issues. In effect, these attacks don't always require strong technical security measures as they could be performed in a more human manner. Combined, these password problems, phishing attacks, credential theft, and social engineering greatly weaken traditional authentication methods. These are all challenges that stress the need for a better and more sophisticated authentication method. Biometric authentication technologies are an opportunity that can help solve the problem by confirming users using their physiological or behavioural features which are hard to steal, share or duplicate. As a result, biometric authentication methods are becoming vital for improving the security and minimizing fraud in today's digital banking landscape.

2. LITERATURE SURVEY

2.1. Fingerprint-Based Authentication Systems

This is because fingerprint-based authentication is easy to implement, economical and highly reliable which is why it's one of the most widely used biometric technologies in the banking and financial sectors today. Fingerprints are particular to each person and have been fairly steady in a person's lifetime and can be utilized for verification of identity. The current fingerprint recognition techniques rely on advanced minutiae extraction and image processing algorithms that extract and match unique ridge features like ridge ending, ridge bifurcation, and ridge patterns. This biometric modality has shown to be effective in researches that have reported authentication accuracy rates

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PP: 01-16.

greater than 95% in controlled environments. The finger print authentication technique is extensively used in mobile banking apps, ATMs and secure financial transactions due to its convenience and speedy user experience. But there are some limitations to the technology like spoofing attacks with fake fingerprints, dirt or moisture contaminating sensors, and problems with performance as a result of skin damage or aging. To mitigate such challenges, researchers have introduced liveness detection systems that employ physiological features like blood circulation, skin structure, and sweat patterns to identify real prints and reject fake ones, improving the security and reliability of these systems.

2.2. Facial Recognition Technologies

With the tremendous strides made in AI, deep learning, and computer vision, face-recognition (FR) has become one of the most popular biometric authentication methods of today. With the rise of smartphone and digital camera devices, the usage of cameras at banks and financial institutions has increased and is accelerating as a tool for mobile banking and customer verification remotely. The latest facial recognition technology uses advanced deep learning algorithms, like Convolutional Neural Networks (CNNs), to identify and interpret facial features, including facial contours, texture patterns, nose shape, and the position of the eyes. The recent advanced architectures like DeepFace, FaceNet, and ArcFace have shown outstanding performance for face recognition in challenging lighting variations, facial expression changes, aging, and face rotation. The use of facial authentication has a number of benefits, such as the ability to operate without contact, being user friendly, and requiring no specialized hardware to complete the identity verification process. Despite these advantages, facial recognition systems are still susceptible to presentation attacks like photographs, videos, masks, and AI-generated deep fake images. Poor lighting, occlusions and camera quality can also influence the recognition performance. In order to achieve better robustness and prevention of fraudulent authentication attempts, researchers have taken care to integrate liveness detection techniques, 3D facial modeling and behavioral analysis methods.

2.3. Multimodal Biometric Systems

Multimodal biometric authentication systems combine two or more biometric attributes to improve authentication accuracy, reliability and security. Multimodal systems are designed to use various biometric features, including facial recognition, fingerprint scanning, iris recognition, voice recognition and palm vein analysis. This integration considerably reduces false acceptance and false rejection rates, and enhances the resistance to spoofing and impersonation attacks. In banking applications, Face + fingerprint, Iris + face, Voice + face and fingerprint + Palm Vein combinations are becoming more common to offer more robust identity verification. The aspects of a typical multimodal authentication system include sequential or parallel acquisition of biometric data, feature extraction, liveness verification, and decision fusion, where the decisions made by the individual modalities are fused to make a final decision. Previous research has demonstrated that a multimodal system has better recognition accuracy, higher fault tolerance and better adaptability to environmental changes than single-modality systems. With the ever-changing nature of cyber threats, unimodal biometric systems are thought of as a potentially useful solution to the security of financial transactions and safeguarding sensitive user data.

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2.4. Research Gap Analysis

While significant advances have been made in biometric authentication technologies, there are still some key challenges that need to be addressed to ensure that biometric authentication is widely adopted and effective in banking applications. The security and privacy of the biometric information is a major issue, as unauthorized access or data leaks can have serious consequences, as biometric identifiers are permanent. What's more, the sophistication of spoofing attacks and AI-generated deepfakes is a major concern for the trustworthiness of current authentication methods. Lack of universal standards and interoperable frameworks for implementing biometric systems in a variety of banking platforms and institutions is also one of the major limitations. Scalability is also difficult to achieve, especially in financial systems running on a massive scale, where millions of users need to be authenticated quickly without impacting performance. Moreover, data protection, user consent and cybersecurity regulations and compliance also add complexities to the deployment of the system. The vast majority of the literature is on the single biometric modality or single security mechanisms, instead of establishing integrated and complete authentication systems. As a result, there is a need for a new generation of more advanced frameworks that integrate a combination of biometric modalities, encryption methods, liveness detection, secure data management, and regulatory requirements into a seamless and comprehensive authentication system that is robust, scalable, and highly secure for modern banking systems.

3. METHODOLOGY

3.1. Proposed Biometric Authentication Framework

3.1.1. User Enrollment Module

The User Enrollment Module is used to enroll new users into the biometric authentication system. At the time of enrollment, the authorized sensors and cameras take biometric information including fingerprints and facial images. Biometric samples are preprocessed, feature extracted and then transformed to secure biometric templates. These templates are then associated with the user and securely stored in the database. The enrollment process must be robust to ensure that biometric data are of high quality and accurate, and that the overall authentication process performs well.

3.1.2. Biometric Acquisition Module

The Biometric Acquisition Module captures real-time information of the users during the authentication process. The module uses devices like fingerprint scanners, smartphones or webcam cameras to take biometric samples. The importance of acquired data is highlighted as the quality of the image can impact the recognition results if the images are not captured properly, due to environmental conditions or improper interaction with the image. Hence, quality assessment mechanism is added in the module to process only valid and usable biometric samples for biometric authentication.

3.1.3. Feature Extraction Module

The Feature Extraction Module analyzes the collected biometric information and extracts features that can be used for identification and verification. Fingerprint recognition involves extracting features like ridge endings and bifurcation points, and facial recognition uses facial landmarks, geometric structures and deep learning based feature vectors. Features are extracted and

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PP: 01-16.

converted to compact digital representations without losing discriminative information, reducing storage size, and computational complexity.

3.1.4. Secure Template Storage

The Secure Template Storage Module (STSM) is intended to safeguard the biometric data of the users against unauthorized access and against cyberattacks. The system does not store raw biometric images, it stores biometric templates which are encrypted after features are extracted from the image. There are advanced encryption techniques and access control mechanisms used to ensure data confidentiality and integrity, along with secure database architectures. This module plays a critical role in addressing privacy concerns and ensuring compliance with data protection regulations in banking environments.

3.1.5. Authentication Engine

The Authentication Engine is the central element of the biometric security framework. It matches the biometric characteristics it captures during the logon or transaction verification process against the ones it has stored in the database. Matching algorithms are used to compute similarity scores and decide if the given biometric information is related to the registered user. The engine is able to incorporate the results of several biometric sources to achieve multimodal authentication and improve the accuracy of the authentication and the risk of unauthorized access.

3.1.6. Decision-Making Module

The Decision-Making Module reviews the results from the authentication engine and returns the final authentication result. It utilizes pre-defined thresholds, fusion strategies and security policies to decide whether to allow or not allow access. In multimodal systems, this module is responsible for the combination of the scores from the various biometric modalities and liveness detection mechanisms to make an accurate decision. The module enhances the security of the system by combining various sources of authentication evidence, reducing false acceptance rates, and providing reliable verification of users in banking applications.

3.2. Biometric Enrollment Process

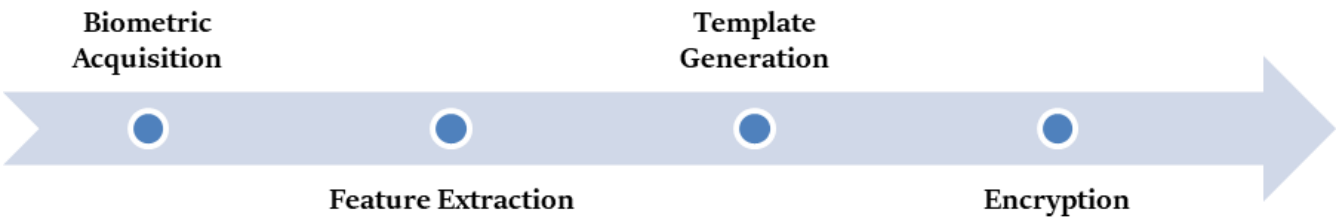

Fig 2 - Biometric Enrollment Process

ISSN: 3071-642X
PP: 01-16.

3.2.1. Step 1: Biometric Acquisition

Biometric enrollment process starts with biometric acquisition, which involves the use of a dedicated device, like fingerprint scanner and a digital camera, to capture the user's biometric data. The high-quality fingerprint image and facial photo are captured by a controlled environment for accurate recognition. The quality of data captured is important as good quality and detailed biometric samples will make the data more useful for future processing and matching activities. This is the first step in establishing a secure biometric identity for each user.

3.2.2. Step 2: Feature Extraction

Once the biometric data is captured, the system extracts features to recognize and distinguish the important attributes of the image of the captured biometric samples. Facial recognition systems analyze facial deep learning feature representations, facial landmarks and contours, whereas for fingerprints, features like ridge ending, bifurcations and ridge patterns are extracted. The biometric images are then fed into machine learning algorithms that extract unique sets of features that can capture an individual's identity with minimal redundancy and noise.

3.2.3. Step 3: Template Generation

After extraction of biometric features, the extracted features are converted to Digital biometric templates. A biometric template is not an image of the fingerprint or face but is a mathematical model of the user's characteristics. This method not only saves storage space but also helps maintain privacy by preventing the reconstruction of the original biometric information. The created templates are used as reference templates for future authentication & identity verification process.

3.2.4. Step 4: Encryption

The system encrypts the biometric templates before they are stored in the database to prevent unauthorized access and cyber attacks. The biometric template is encrypted into a secure format to be accessible and interpretable only by the authorized parts of the authentication system. This security can help protect data privacy, prevent template stealing, and enforce data privacy laws. The system ensures that the storing of biometric data is secured, which greatly diminishes the chances of fraud and data breaches.

3.3. Authentication Process

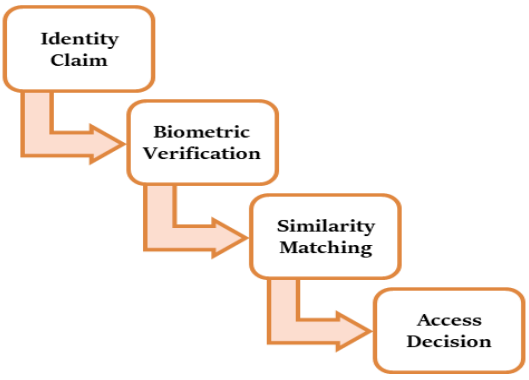

Fig 3 - Authentication Process

ISSN: 3071-642X
PP: 01-16.

3.3.1. Stage 1: Identity Claim

The authentication process starts when the user tries to access the banking system using a mobile banking application, web portal or ATM interface and the identity claim stage. The user enters an identifier, like a username, registered mobile number, customer ID, or account number at this stage. This information is used to locate the corresponding biometric templates in the biometric database and to start the verification process. The identity claim is a declaration by the user that will be used as a first step towards establishing the user's right to be authenticated before the actual biometric authentication process.

3.3.2. Stage 2: Biometric Verification

After the identity claim is verified, the system will verify the identity through biometric verification, which will include capturing the user's fingerprint and facial information in real-time. The fingerprint image is captured by a fingerprint sensor and the face image of the user is captured by a camera and analysed. The collected biometric samples are preprocessed to enhance the image quality and eliminate noise. In the system, the relevant features are then extracted from both biometric modalities and then prepared for comparison with the enrolled biometric templates. This stage is designed to ensure that the authentication process is based on distinguishing physical features that can't be easily mimicked or duplicated.

3.3.3. Stage 3: Similarity Matching

At the similarity matching phase, the authentication engine performs a similarity matching with the extracted biometric features and the matching biometric features stored in the secure database. The similarity score is used in advanced matching algorithms to show how close the data to match with the data enrolled. Matching scores can be generated individually for fingerprint and face recognition, and the scores for multimodal systems can be fused using different techniques. This is essential for the accuracy of this stage, as it impacts the reliability and effectiveness of the authentication process.

3.3.4. Stage 4: Access Decision

The access decision process is the last step in the authentication process in which the matching engine produces a set of similarity scores that are compared to a set of thresholds that were defined to be accepted. Once the required threshold values are met or exceeded, the user's identity is confirmed and access to banking services provided. If the scores are not in the threshold, authentication will be denied, and access will be denied. For multimodal biometric systems, the decision could also include liveness detection outputs and security policies to make sure only the legitimate users are authenticated. This phase offers a secure and reliable way to safeguard delicate banking transactions and banking information.

3.4. Performance Evaluation Metrics

The proposed multimodal biometric authentication system is assessed by adopting some of the most commonly used performance measures that are used to measure the accuracy, reliability,

ISSN: 3071-642X
PP: 01-16.

and security of the system. One of them is the False Acceptance Rate (FAR) – the percentage of non-authorized users that are falsely accepted by the authentication system. To calculate the FAR, the number of false acceptances is divided by the total number of authentication attempts and the result is multiplied by one hundred. A lower FAR indicates a more secure system as it minimizes the risk of unauthorized access to the sensitive banking service and the customer's information. A critical one is the False Rejection Rate (FRR), which is the proportion of acceptable users that are rejected during the authentication process. FRR is calculated as a percentage by dividing the number of false rejections by the authentication attempts, and multiplying by 100. A low FAR can increase security but it is also essential to have a low FRR to avoid that too many legitimate users are rejected, thus degrading satisfaction and usability. Hence, a biometric system needs to provide security and usability of the system in an adequate manner. The overall performance of the authentication framework is also evaluated by the Accuracy which is the ratio of correct classification of the authentication attempts done by the system. The accuracy is the ratio of correctly authenticated objects to the total number of authentication attempts, multiplied by one hundred. The higher the accuracy value, the more effective the biometric system is at differentiating between authorized and unauthorized users, which is ideal for banking applications where reliable identity verification is crucial. The Equal Error Rate (EER) is also a widely used performance measure of biometric systems along with FAR, FRR and Accuracy. EER is the operating point where the False Acceptance Rate and False Rejection Rate are equal. The lower the EER number the more effective the system will be overall and the more balanced the security/usability will be. As a result, EER is considered one of the most significant criteria to assess and compare biometric authentication systems in research and practical applications.

4. RESULTS AND DISCUSSION

4.1. Experimental Setup

The proposed multimodal biometric authentication system was tested using an extensive experimental test bed which was designed to simulate the operational conditions in a contemporary digital banking system. The test was conducted using a multimodal biometric database with fingerprint and face biometric samples of registered users. The setting for the experiment involved emulating real banking activities in which customers used mobile application, internet banking portals, and other electronic banking channels to avail themselves of banking services. The main aim of the experiment was to evaluate the proposed framework based on the accuracy of authentication, level of security, False Acceptance Rate (FAR), False Rejection Rate (FRR), system convenience and overall system reliability. The users were given a range of authentication tasks in scenarios that closely simulated real banking conditions, including certain scenarios in which they failed to do so.Users were given a variety of authentication tasks under a number of scenarios, including some cases where they didn't successfully complete the task, to emulate real banking situations. The system design included a machine learning-based authentication engine that was tasked with matching biometric features and verifying identities. For fingerprint authentication, advanced minutiae-based feature extraction methods were used to extract the minutiae from the captured image and for facial authentication, advanced Convolutional Neural Network (CNN) algorithms were employed which

ISSN: 3071-642X
PP: 01-16.

were able to extract the discriminative facial features for accurate recognition. Biometric templates obtained during enrolment were encrypted prior to storage in the database to improve security and privacy of users' biometric information. Liveness detection mechanisms were also included in the fingerprint and facial recognition modules to detect and thwart spoofing attacks utilizing prints, digital images, masks, videos and fake fingerprints. This made sure that the only samples accepted for authentication were valid biometric samples. The experimental data set comprised a broad spectrum of test conditions to test the strength of the proposed framework. The effect of actual deployment scenarios, including lighting conditions, facial expressions, camera orientation, fingerprint orientation and device configuration, was introduced to study the performance of the systems. To produce statistically meaningful results, over 10,000 attempts were simulated, both successful and not, of authentication. The performance of the proposed multimodal biometric framework was then evaluated against the traditional password based authentication and unimodal biometric authentication systems. The comparative analysis helped determine if combining multiple biometric modalities could greatly boost authentication accuracy, minimize security vulnerabilities, mitigate spoofing attacks, and offer a more secure and convenient solution for today's banking applications.

4.2. Performance Comparison of Authentication Methods

Table 1: Performance Comparison of Authentication Methods

Authentication Method	Accuracy (%)	Security Strength (%)	User Convenience (%)	Spoof Resistance (%)	Overall Performance (%)
Password-Based Authentication	82	75	70	60	72
Fingerprint Authentication	95	92	94	88	92
Facial Recognition Authentication	94	90	96	85	91
Iris Recognition Authentication	97	96	85	95	93
Multimodal Biometric Authentication	99	98	97	98	98

4.2.1. Password-Based Authentication

The accuracy of password based authentication was 82%, the security strength was 75%, the user convenience was 70%, the level of spoof resistance was 60% and the overall performance was 72%. While passwords are still the primary form of authentication in banking systems, they can face many security challenges like phishing attacks, password guessing, credential theft and brute-force attacks. Users are also likely to have weak passwords or use the same password for several online platforms, further compounding security issues. Although it is relatively easy to implement and maintain password-based systems, the fact that its security and usability scores were lower than

ISSN: 3071-642X
PP: 01-16.

other systems shows that there are significant weaknesses in protecting sensitive banking information.

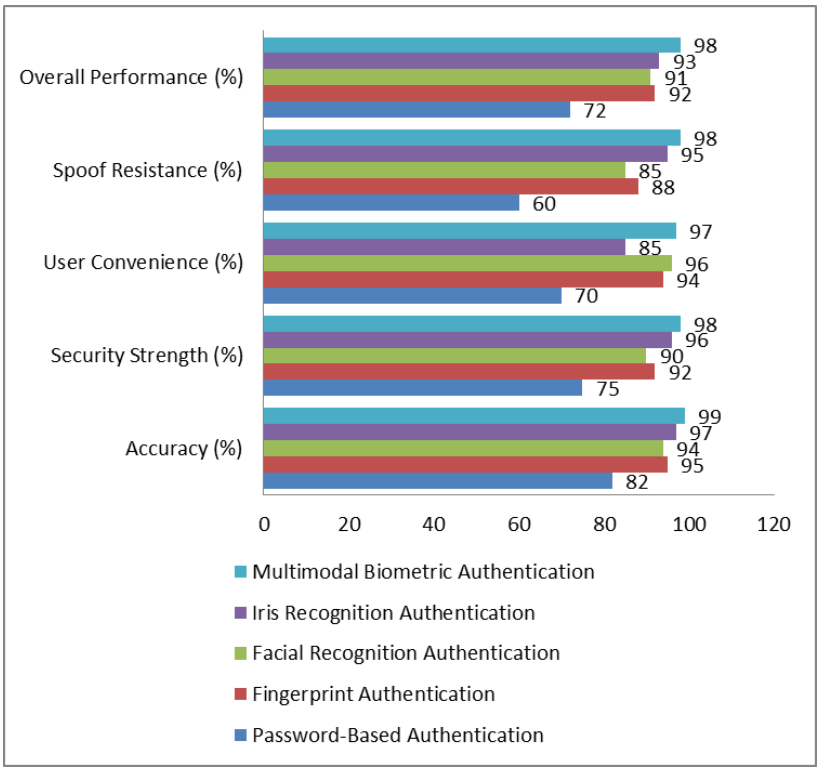

Fig 4 - Performance Comparison of Authentication Methods

4.2.2. Fingerprint Authentication

The results for the Fingerprint authentication system showed good performance with 95% accuracy, 92% security strength, 94% user convenience, 88% spoof resistance, and an overall performance score of 92%. Fingerprint patterns are unique and permanent, making them a very reliable biometric modality for verifying identity. In mobile banking systems with fingerprint sensors, fingerprint authentication provides swift access and a seamless user experience. Nevertheless, even with its high levels of accuracy, the system can be vulnerable to sophisticated spoofing attacks with artificial fingerprint replicas, if advanced liveness detection is not in place.

4.2.3. Facial Recognition Authentication

The accuracy rate of the facial recognition authentication was recorded at 94%, security strength of 90%, user convenience of 96%, and spoof resistance of 85% and overall performance score of 91%. This is a highly convenient and contactless authentication method. Fast and convenient authentication by only looking at a camera. In recent years, the accuracy of recognition has greatly improved due to the progress in deep learning and computer vision. However, facial recognition systems can be influenced by environmental conditions like lighting, camera quality, facial expression, photo or video presentation attacks etc., which can affect the overall security.

ISSN: 3071-642X
PP: 01-16.

4.2.4. Iris Recognition Authentication

The performance score of Iris recognition authentication was 93% – excellent, the security strength was 96%, the user convenience was 85%, the spoof resistance was 95% and the accuracy was excellent – 97%. Highly distinct and stable patterns in the iris offer unparalleled accuracy in identification. Iris recognition is considered to be one of the most secure biometric authentication systems because of its uniqueness. The Technology provides excellent protection against unauthorized access and spoofing. Specialized imaging equipment is often needed, however, and some users might not be as convenient as fingerprint or facial recognition systems.

4.2.5. Multimodal Biometric Authentication

The proposed multimodal biometric authentication framework had the highest accuracy with 99%, security level with 98%, user convenience with 97%, spoof resistance with 98% and overall performance with 98% among all of the evaluated methods. The framework uses a combination of fingerprint and facial recognition technologies and implements liveness detection mechanisms that capitalize on the benefits of both modalities and reduce the weaknesses of each. Combining several authentication factors also helps to reduce the number of false acceptances and rejections, making the system more resistant to spoofing attacks and deepfakes, and increases the reliability of the system. The experimental findings show that multimodal biometric authentication offers a greater security, higher accuracy and greater user-friendliness solution for digital banking applications, outperforming the traditional password-based and single-biometric authentication systems.

4.3. Discussion

The results of the experiments are clear and unambiguous; biometric authentication technologies offer significant benefits over traditional password-based authentication in today's digital banking landscape. Overall, the traditional password authentication system was the worst performer of the authentication techniques evaluated, mainly due to the many cyber attacks against it including phishing, password reuse, keylogging, credential theft, and brute-force attacks. Because password security is dependant on user generated and maintained strong passwords, human error frequently diminishes password security. Cyberattacks are becoming more sophisticated and using passwords alone isn't enough to secure vital banking data and financial transactions. Fingerprint authentication showed promising results in terms of accuracy, security, and user-friendliness when compared with other biometric methods assessed. Fingerprint sensors have been made available in a wide range of devices, such as smartphones and devices used in financial transactions, which has led to their widespread use in financial applications. While fingerprint recognition can be used to verify identity quickly and accurately, sophisticated fingerprint spoofing attacks with artificial fingerprints can defeat it. By incorporating liveness detection features, the technology enhances security by validating that only real biometric samples are used for authentication. Facial recognition authentication also showed a high degree of convenience and accessibility as it allows to contactlessly verify the user. The development in deep learning and computer vision has significantly boosted the accuracy of facial recognition, which is applicable in mobile and online banking services. However, if not effective measures are taken, the environmental conditions like poor light conditions, variations

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PP: 01-16.

in camera quality, facial occlusion and presentation attack using photographs or video may cause the recognition to be inaccurate. Iris pattern recognition had outstanding accuracy and security results because of the uniqueness and stability of iris patterns. It is one of the most secure biometric modalities due to its resistance to spoofing attacks. But, it may not be readily adopted in large-scale consumer banking application space due to the need for specialized imaging hardware and higher implementation cost. The proposed multimodal biometric authentication framework, on the contrary, is able to effectively combine the best of several biometric features and overcome their drawbacks. The framework included fingerprint recognition, facial recognition, liveness detection, encrypted template storage, and machine learning-based matching algorithms, and outperformed all other frameworks in all the evaluation metrics. Multimodal biometric approaches provide a multi-layered security approach, leading to much lower rates of false acceptance and false rejection, and improving resistance to spoofing and deepfake attacks. Additionally, the encryption of biometric template storage offers strong security measures against any unauthorized access, data breaches, and template reconstruction attacks, ensuring privacy and security concerns are tackled with critical attention. Machine learning authentication methods further enhance the recognition performance by learning and adapting to the variations in the biometric characteristics of the users over time. Indeed, the experimental results have shown that multimodal biometric authentication can be a practical, scalable and very secure solution for future digital banking systems. By implementing these frameworks, financial institutions can reinforce their fraud prevention measures, boost customer confidence, improve user experience, and maintain a safe and secure environment for accessing digital financial services in today's intricate cybersecurity landscape.

5. CONCLUSION

Digital banking and online financial services have evolved at a rapid pace, changing the way customers are interacting with banks and allowing them to access financial services from a distance, anytime and anywhere. But the digital transformation has also come with rising vulnerability to cybersecurity threats, and secure user authentication has become an essential feature in safeguarding financial information. For many years, the most common ways to verify users have been by using a password, a Personal Identification Number (PIN), or a security question. Although these methods are widely adopted, they have big drawbacks such as phishing, password reuse, brute force attacks, credential theft and social engineering attacks. Traditional authentication methods are proving to be increasingly ineffective in protecting today's banking systems, as cybercriminals are increasingly devising new and more complex attack methods. As a result, biometric authentication technologies have become an appealing solution that can offer more secure level of security while improving the user experience and usability of the device.

This study considered the use of biometric authentication technologies in digital banking and analyzed the effectiveness of various biometric modalities such as fingerprint recognition, facial recognition, iris recognition, and multimodal biometric authentication systems. The literature review identified that each biometric modality has its own pros and cons. Iris recognition has excellent security because iris patterns are unique and stable, fingerprint recognition provides high accuracy

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and ease of implementation, and facial recognition offers contactless and user-friendly authentication. But, there are challenges for each individual biometric modality, such as spoofing attack, environmental factors, hardware requirement, and operational constraints. The results highlight the importance of implementing comprehensive authentication systems that can exceed the capacities of stand-alone biometric-based systems.

To overcome these difficulties, this research aimed to design a complete multimodal biometric authentication framework which integrates fingerprint verification, liveness detection, machine learning matching algorithms, biometric template encryption, and facial recognition. Combining various biometric attributes forms a multi-layered security system that greatly improves the accuracy of authentication and prevents unauthorized access. Liveness detection mechanisms also enhance security, rendering photos, videos, deepfakes, masks and artificial fingerprint replicas ineffective. Furthermore, encrypted template storage helps to safeguard the confidentiality and integrity of biometric data, minimizing the chances of data breaches and identity theft. The use of machine learning techniques enhances the accuracy of matching by effectively dealing with the natural variations in biometric traits and adjusting to evolving user conditions.

The experimental assessment proved that the proposed multimodal framework achieves a high level of authentication accuracy of 99%, which is higher than the traditional password-based systems and single-biometric authentication systems. The frame was also found to be more secure, more resistant to spoofing, more convenient to use by the user, and performed better in terms of the overall system performance. The results show that by using several biometric modalities together, the False Acceptance Rate (FAR) and False Rejection Rate (FRR) are drastically reduced, providing more accurate user verification and better security against cyber threat. Moreover, the suggested system offers a realistic as well as scalable remedy for implementation in real-world banking settings where security as well as user experience are crucial factors.

A major impact of this research is the focus on privacy preserving biometric security and secure handling of templates. However, with the increasing stringent regulations on biometric data protection by governments and regulatory bodies, financial institutions will have to implement strong security measures and ensure that their architectures are compliant with privacy policies. Strong encryption methods, access controls, and privacy-preserving authentication protocols will be essential to keeping users' trust and meeting regulatory standards. It is, therefore, crucial that the future banking authentication system be not only secure, but also take into consideration ethical, legal and privacy issues related to biometric data processing. A number of new technologies are in the pipeline with the potential to improve biometric authentication systems in the future. Incorporating AI and deep learning will enhance recognition accuracy and adaptive decision-making further. Decentralized and tamper-proof identity verification can be achieved through blockchain-based identity management. These capabilities can be used to improve the level of privacy in biometric data, and collaborative model training without the sharing of sensitive biometric data can be achieved through federated learning.Federated learning can support the collaborative training of

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models without sharing sensitive biometric data, and privacy-preserving biometrics can help increase the protection of the data. Also, there are ongoing behavioral authentication methods that observe patterns in customer behavior, like typing attributes, and interaction habits with devices that could offer continuous security in addition to login verification. Combining these cutting-edge technologies could lead to the development of sophisticated authentication systems that are both intelligent, scalable, and resilient, solving the challenges of the future in cyber security. Finally, biometric authentication is an innovative and powerful way to protect today's digital banking. Biometric systems offer greater security than traditional means of authentication due to their unique physiological features that enable identity verification, thereby preventing fraud, unauthorized access and identity theft. The results of this research show the implementation of multimodal biometric authentication with liveness detection, encryption and machine learning methods provides the best combination of security, accuracy, privacy and convenience for the user. The integration of advanced biometric authentication systems is expected to be a key element in creating secure, trustworthy, and resilient financial ecosystems that can adapt to the evolving needs of the digital age.

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