B.M.S. COLLEGE OF ENGINEERING

(Autonomous College under VTU)

Bull Temple Road, Basavangudi, Bangalore - 560019

NeuroShield:Cancelable Biometric Key Generation from EEG for Secure Authentication

22IS8PWPP2

Report

ON

NeuroShield

Submitted by

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in

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Under the Guidance of

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DECLARATION

We, hereby declare that the Assignment Report entitled ***NeuroShield:Cancelable Biometric Key Generation from EEG for Secure Authentication"*** on **Capstone Project (22IS8PWPP2)** is a bonafide work and has been carried out by me under the guidance of Dr. Mamatha K R, Associate Professor, Department of ISE, B.M.S. College of Engineering, Bengaluru, in partial fulfillment of the requirements of the degree of Bachelor of Engineering in Information Science & Engineering of Visvesvaraya Technological University, Belagavi. I further declare that, to the best of my knowledge and belief, this report has not been submitted either in part or in full to any other university/college.

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Abstract

In an era of escalating cybersecurity threats and growing concerns over biometric privacy, this report presents *NeuroShield*—a novel framework for secure and reusable authentication based on electroencephalography (EEG) signals. Unlike traditional biometrics, EEG-based authentication leverages the inherent uniqueness and liveness of brainwave patterns, making it highly resistant to spoofing and replay attacks. *NeuroShield* introduces a privacy-preserving and cancelable biometric system that transforms EEG features into cryptographic keys, enabling revocability and protecting the underlying biometric data from inversion threats.

By leveraging the intrinsic liveness and non-replicability of EEG signals, *NeuroShield* addresses critical limitations of traditional biometric systems, such as irreversibility and susceptibility to theft or misuse. The system capitalizes on the dynamic nature of brain signals, which vary subtly across sessions yet retain identifiable patterns, enabling not only secure authentication but also periodic key refreshment. This adaptability ensures that biometric templates can be updated without compromising the user's identity, offering a robust solution to long-standing privacy and permanence concerns in biometric security.

The framework integrates signal preprocessing, feature extraction, quantization, and secure key generation into a cohesive pipeline, supported by a Flask-based web interface and a PostgreSQL database. Experimental results from simulated EEG data demonstrate high intra-session reliability, low false acceptance/rejection rates, and strong resilience to adversarial attempts. Furthermore, the system supports key regeneration and cancellation without compromising identity integrity, offering long-term usability in dynamic security environments.

This report underscores the potential of brain-computer interface (BCI) technologies in reshaping digital authentication by uniting neuroscience with modern cryptographic principles. With promising applications in healthcare, IoT, and immersive environments, *NeuroShield* lays the foundation for next-generation, mind-driven security systems that prioritize both trust and adaptability.

1 Introduction

In the evolving landscape of cybersecurity, the quest for more secure and user-centric authentication methods has led to the exploration of biometric systems that leverage unique physiological and behavioral characteristics. Among these, electroencephalography (EEG)-based authentication has emerged as a promising frontier, offering a blend of security and user convenience. EEG captures the electrical activity of the brain, providing a rich source of data that is inherently unique to each individual, making it an ideal candidate for biometric authentication systems.

The concept of using brainwave patterns for authentication is not entirely new. Researchers have long been intrigued by the potential of EEG signals in identifying individuals based on their neural responses to specific stimuli. Studies, such as those conducted at Carleton University, have demonstrated that even when thinking of the same thing, the brain's measurable electrical impulses vary slightly from person to person, suggesting that brainwaves carry distinctive individual signatures.

Implementing an EEG-based authentication system typically involves three critical phases: user enrollment, authentication, and key generation. During the enrollment phase, users are prompted to engage in specific mental activities, such as reading, writing, or imagination. The EEG signals generated during these tasks are recorded and processed to extract distinctive features, which are then stored as a user template in a structured format such as JSON. This template serves as a reference for future authentication attempts.

The authentication phase involves capturing EEG signals as the user performs the same mental task registered during enrollment. These signals are processed to extract features, which are then compared against the stored template using machine learning classifiers. Support Vector Machines (SVMs) are commonly employed in this context due to their effectiveness in handling high-dimensional data and their robustness to overfitting. SVMs work by finding the optimal hyperplane that separates different classes in the feature space, making them suitable for distinguishing between genuine users and impostors.

Upon successful authentication, the system proceeds to the key generation phase. Here, the extracted EEG features are vectorized and binarized to form a binary key, which is then subjected to cryptographic hashing. This hashed key can be securely stored in a database, such as PostgreSQL, and used for various cryptographic applications. Notably, some systems avoid storing the key altogether by generating it anew from each EEG signal, enhancing security by

eliminating the risk of key compromise.

A critical aspect of EEG-based authentication systems is their adaptability to changes in a user's mental state or memory. To address scenarios where a user may forget the specific mental task registered during enrollment, the concept of cancelable biometrics is introduced. Cancelable biometrics involve the intentional and systematically repeatable distortion of biometric features, allowing for the revocation and replacement of compromised templates. In the context of EEG, this means that if a user forgets their registered mental task, they can perform a new task, and the system can generate a new template, effectively "canceling" the old one.

The implementation of such a system requires a robust technological stack. Python, with its extensive libraries for signal processing and machine learning, serves as an ideal choice for backend development. Flask, a lightweight web framework, facilitates the creation of web applications that can interact with the EEG processing modules. For the frontend, HTML, CSS, and Bootstrap CSS provide the tools necessary to build responsive and user-friendly interfaces. This combination ensures that the system is not only functionally robust but also accessible and easy to use.

The potential applications of EEG-based authentication systems are vast. In high-security environments, such systems can provide an additional layer of security that is difficult to replicate or forge. In consumer electronics, they can offer a seamless and secure method for user authentication, enhancing user experience while maintaining security. Moreover, the continuous nature of EEG signals opens avenues for continuous authentication, where the system continuously verifies the user's identity, providing real-time security monitoring.

Despite the promising prospects, EEG-based authentication systems face several challenges. The variability of EEG signals due to factors like fatigue, stress, or environmental noise can affect the consistency of the extracted features. Ensuring the reliability of the system under varying conditions requires sophisticated signal processing techniques and robust machine learning models. Additionally, the need for EEG hardware, which may be cumbersome or expensive, poses a barrier to widespread adoption. However, advancements in wearable EEG technology are gradually mitigating this issue, making EEG acquisition more accessible and user-friendly.

In conclusion, EEG-based authentication represents a significant advancement in biometric security, offering a unique blend of security, adaptability, and user convenience. By leveraging the distinctiveness of brainwave patterns and incorporating mechanisms like cancelable biometrics, such systems can provide robust and flexible authentication solutions. While challenges remain, ongoing research and technological advancements continue to pave the way for the practical implementation of EEG-based authentication in various domains.

1.1 Background

The increasing frequency of cyberattacks, data breaches, and identity theft in recent years has underscored a critical need for secure, reliable, and user-centric authentication mechanisms. Traditional security systems, which rely on passwords, tokens, or PINs, are increasingly vulnerable to being hacked, forgotten, or stolen. These legacy systems are not only susceptible to external attacks but also place a considerable cognitive burden on users, who must remember complex passwords or carry physical security devices.

In response, biometric authentication systems have emerged as a highly promising solution, leveraging inherent physiological or behavioral traits such as fingerprints, facial features, and iris patterns. While these systems offer improved security, they are not immune to spoofing or coercion-based attacks. In contrast, EEG-based authentication systems provide a novel paradigm that is significantly harder to duplicate or manipulate, as they operate on brain activity that is both unique and dynamic to each individual.

Electroencephalography (EEG) involves recording the electrical activity of the brain using sensors placed on the scalp. This activity reflects a range of cognitive processes, including attention, perception, memory, and thought. Unlike physical biometric traits, brain signals are not externally visible or easily captured without the user's consent. This makes EEG-based biometrics inherently secure against most conventional spoofing attacks. Furthermore, the variability and complexity of EEG signals offer a highly individualized biometric signature that can be fine-tuned to specific mental activities.

The core premise of using EEG in authentication is rooted in the idea that each individual's brain produces distinct patterns in response to particular cognitive tasks. When a person thinks about reading, writing, or imagining, their EEG signals produce measurable responses that differ not only between individuals but also among different activities. This opens up the possibility of using cognitive tasks as a mental "password," known only to the user and intrinsically tied to their neural activity.

The development of EEG-based authentication systems is motivated by several important considerations. First and foremost is security. Unlike a password, which can be written down, shared, or guessed, a person's brainwave pattern cannot be duplicated easily. The dynamic nature of EEG signals adds another layer of unpredictability, which enhances the resilience of the system against attacks.

Secondly, these systems offer privacy. Since brainwave patterns are unique and largely inaccessible without the user's participation, the risk of unauthorized data acquisition is signif-

icantly reduced. Third, EEG systems have the potential to support continuous authentication, unlike most conventional biometrics that perform a one-time verification. Continuous monitoring of EEG signals can ensure that the authenticated user remains present and active, thus adding another layer of protection in sensitive applications like finance, healthcare, and critical infrastructure.

A deeper look into the architecture of an EEG-based neuro key generation system reveals a highly integrated, multi-phase pipeline. The first phase is user enrollment, in which the user is guided to think of a specific cognitive activity—such as imagining a story, mentally writing a sentence, or silently reading a passage. The EEG signals captured during this phase are subjected to pre-processing steps including filtering, artifact removal, and normalization.

This is followed by feature extraction, wherein meaningful components of the EEG signal are isolated using techniques like wavelet transforms, power spectral density estimation, or principal component analysis. These features are encapsulated into a structured template, commonly stored in JSON format, representing the unique cognitive signature of the user.

The second phase, authentication, involves a repeat of the cognitive task during a login session. New EEG data are captured and compared to the stored template using a machine learning classifier, typically a Support Vector Machine (SVM), which has been trained to recognize the user's specific brain activity patterns with high accuracy.

The final and most innovative component is the key generation phase. Here, the features derived from the authenticated EEG signal are used to produce a secure cryptographic key. This process involves vectorizing and binarizing the feature set to obtain a unique binary string, which is then hashed using cryptographic algorithms like SHA-256. The hashed key can serve multiple roles: it may be used for file encryption, secure communication, or simply stored in a PostgreSQL database for verification purposes.

This approach ensures that the cryptographic key is never statically stored; instead, it is generated on-the-fly from the user's mental state, providing a robust method of ephemeral security. One of the key innovations of this system is its non-reusability and renewability, made possible through the concept of cancelable biometrics. If a user forgets their original mental activity, or if the system is compromised, a new activity can be imagined and enrolled, thereby updating the stored template and effectively rendering the old one useless.

The development and deployment of such a system require a balanced fusion of hardware, software, and user interface design. On the backend, Python serves as the foundational programming language due to its rich ecosystem of libraries in signal processing, machine learning, and data analysis. Frameworks like SciPy, NumPy, scikit-learn, and MNE are used extensively

in signal pre-processing, feature engineering, and classification. Flask provides the web server layer, enabling secure interactions between the EEG device, machine learning module, and database layer.

On the frontend, HTML and CSS are employed alongside Bootstrap CSS to ensure a responsive and intuitive interface that accommodates real-time EEG feedback, user prompts, and authentication results. PostgreSQL offers a scalable and secure relational database for storing user templates and metadata, ensuring the system remains consistent and reliable under varying loads.

Beyond technical implementation, it is essential to understand the broader societal and operational implications of deploying such a neuro-biometric system. In an age of increasing digital surveillance and data commodification, EEG-based authentication offers a path toward personal empowerment, allowing individuals to take control over their digital identities through something as intrinsic and private as their thoughts. It redefines the very notion of a password by making it inseparable from the cognitive state of its owner.

Furthermore, this technology can be particularly beneficial in scenarios requiring high assurance identity verification, such as in defense sectors, space missions, or medical applications, where conventional biometrics may fall short.

Despite the promise, EEG-based systems are not without limitations. The requirement for EEG hardware, although becoming more affordable and compact, may still present barriers to mainstream adoption. Additionally, variability in signal quality due to emotional state, environmental noise, or electrode placement can affect performance.

Addressing these challenges necessitates the development of robust signal normalization algorithms, artifact removal techniques, and adaptive classifiers that can learn and evolve over time. Research into improving dry-electrode EEG caps and reducing setup time is ongoing and will play a crucial role in the scalability of such systems.

In sum, the neuro key generation system based on EEG signals offers a compelling vision for the future of secure and personalized authentication. It brings together advanced concepts from neuroscience, machine learning, and cryptography into a unified framework capable of addressing many of the weaknesses of traditional security mechanisms. Its adaptability, non-replicability, and capacity for real-time authentication make it suitable for a wide range of high-security applications.

As EEG technology becomes more user-friendly and computational models more sophisticated, the line between the brain and the digital world continues to blur—ushering in an era where thought itself becomes the key to identity and security.

1.2 Motivation

In the contemporary digital era, the proliferation of online services and the increasing reliance on digital platforms have underscored the paramount importance of robust and reliable authentication mechanisms. Traditional authentication methods, such as passwords and personal identification numbers (PINs), have long been the cornerstone of user verification. However, these methods are fraught with vulnerabilities, including susceptibility to phishing attacks, brute-force attempts, and social engineering tactics. Moreover, the human tendency to reuse passwords across multiple platforms exacerbates the risk of unauthorized access, leading to significant data breaches and financial losses.

Biometric authentication has emerged as a compelling alternative, leveraging unique physiological and behavioral traits to verify identity. Common biometric modalities include fingerprints, facial recognition, iris scans, and voice patterns. While these methods offer enhanced security over traditional credentials, they are not impervious to spoofing or replication. For instance, high-resolution images can deceive facial recognition systems, and latent fingerprints can be lifted and reproduced. Furthermore, once compromised, biometric data cannot be changed, unlike passwords, posing a significant risk to user privacy and security.

In this context, electroencephalography (EEG)-based authentication presents a novel and promising avenue. EEG captures the electrical activity of the brain, providing a dynamic and intrinsically unique biometric signature. Unlike external biometric traits, brainwave patterns are inherently concealed and challenging to replicate without the individual's active participation. This characteristic renders EEG-based authentication highly resistant to spoofing and coercion, addressing some of the critical shortcomings of existing biometric systems.

The concept of utilizing EEG signals for authentication is grounded in the principle that each individual's brain responds distinctively to specific stimuli or cognitive tasks. When a person engages in activities such as reading, writing, or imagination, their brain generates unique electrical patterns that can be captured and analyzed. These patterns, influenced by factors like neural pathways, cognitive processing styles, and personal experiences, serve as a robust basis for identity verification.

Implementing an EEG-based authentication system involves several critical phases. The initial phase, user enrollment, entails capturing EEG signals while the user performs a designated mental task. These signals undergo preprocessing to remove artifacts and noise, followed by feature extraction to identify salient characteristics. The extracted features are then stored as a user-specific template in a structured format, such as JSON.

The subsequent authentication phase requires the user to perform the same mental task, during which new EEG data is collected and processed. A machine learning classifier, such as a Support Vector Machine (SVM), compares the new data against the stored template to determine identity verification. SVMs are particularly suited for this application due to their ability to handle high-dimensional data and their robustness in classification tasks.

Upon successful authentication, the system proceeds to the key generation phase. Here, the extracted EEG features are vectorized and binarized to form a unique binary key. This key undergoes cryptographic hashing, ensuring secure storage and transmission. The hashed key can be stored in a PostgreSQL database and used for various cryptographic applications, such as secure communication or data encryption.

A notable feature of this system is the incorporation of cancelable biometrics. Recognizing that users may forget their designated mental tasks or that templates may become compromised, the system allows for the regeneration of biometric templates. By performing a new mental task, users can generate a new EEG pattern, effectively replacing the previous template. This flexibility enhances the system's resilience and user-friendliness, addressing a significant limitation of traditional biometric systems.

The integration of EEG-based authentication into practical applications necessitates a robust technological infrastructure. Python, with its extensive libraries for signal processing and machine learning, serves as the backbone for backend development. Flask provides a lightweight web framework for building the application's interface, while HTML, CSS, and Bootstrap CSS ensure a responsive and user-friendly frontend. PostgreSQL offers a reliable and scalable database solution for storing user templates and related data.

The potential applications of EEG-based authentication are vast and varied. In high-security environments, such as military installations or research facilities, the need for robust and tamper-proof authentication mechanisms is paramount. EEG-based systems offer a level of security that is difficult to achieve with traditional methods. In the healthcare sector, where patient data confidentiality is critical, EEG authentication can provide secure access to electronic health records. Additionally, in the realm of personal computing, EEG-based login systems can enhance user privacy and security.

Despite its promise, EEG-based authentication faces several challenges. The variability of EEG signals due to factors like fatigue, stress, or environmental noise can affect the consistency of the extracted features. Ensuring the reliability of the system under varying conditions requires sophisticated signal processing techniques and adaptive machine learning models. Moreover, the need for EEG hardware, which may be cumbersome or expensive, poses a barrier

to widespread adoption. However, advancements in wearable EEG technology are gradually mitigating this issue, making EEG acquisition more accessible and user-friendly.

In conclusion, the motivation for developing an EEG-based neuro key generation system is rooted in the quest for secure, reliable, and user-centric authentication mechanisms. By leveraging the unique and dynamic nature of brainwave patterns, such systems offer a compelling alternative to traditional authentication methods. The integration of cancelable biometrics further enhances the system's flexibility and resilience, addressing critical limitations of existing biometric systems. As technology continues to evolve, EEG-based authentication holds the potential to redefine the landscape of digital security, offering a harmonious blend of innovation, security, and user empowerment.

1.3 Importance

The rapid evolution of digital technology and its integration into every facet of human life has brought about a parallel need for increasingly sophisticated and secure methods of user authentication. Traditional security systems, such as passwords and physical tokens, have become inadequate in the face of growing cyber threats, data breaches, and identity theft. As a result, the field of biometric authentication has emerged as a critical area of research and innovation. Within this domain, the EEG-based neuro key generation system represents a significant advancement—not just technically, but also in how it redefines personal identity, cognitive privacy, and security.

The importance of EEG-based authentication begins with its foundation in neurophysiology. Unlike conventional biometric traits such as fingerprints or facial recognition, brainwave patterns are not observable, cannot be duplicated by simple means, and require conscious engagement from the user. This makes them inherently secure and resistant to spoofing or impersonation. More importantly, brain signals are generated uniquely for each individual in response to specific thoughts or cognitive tasks, making them dynamic rather than static. This dynamic nature of EEG patterns enables systems not only to authenticate identity but to do so in a context-aware and activity-specific manner. It is a breakthrough approach to biometrics, placing cognition at the heart of authentication rather than merely physical traits.

Another key importance of this system lies in its non-invasive yet high-entropy biometric data. EEG signals can be captured using non-invasive electrodes placed on the scalp, making the process user-friendly and safe. At the same time, the entropy of the data—essentially, its randomness and complexity—is far higher than many traditional biometric modalities. This makes EEG an excellent source for generating cryptographic keys. Since each person's brain

activity is complex and unique, the system can produce strong, individualized keys that cannot be guessed, reverse-engineered, or regenerated by attackers. This serves as a natural basis for secure cryptographic systems that move beyond passwords and static tokens.

The incorporation of EEG signals into key generation and cryptographic operations also introduces a transformative shift in how identity is coupled with secure access. Unlike conventional systems where the key is stored and managed externally, EEG-based systems tie the key generation directly to the user's cognitive state. This "on-the-fly" generation ensures that no actual key is stored or transmitted in its raw form, thus reducing the attack surface. A compromised system cannot leak stored credentials because the credentials are never statically stored. In essence, the key exists only in the moment it is needed and only in the mind of the user. This ephemeral nature of security credentials is of immense importance in environments where persistent storage may be risky or in applications where security must be exceptionally high.

The cognitive personalization of security systems also enhances user trust and ownership. When authentication is linked to a unique mental activity—such as imagining a shape or silently reading a familiar phrase—the process becomes more than a technical interaction; it becomes a deeply personal act. Users are no longer passive participants using assigned passwords or externally determined biometric traits. Instead, they actively define their security through mental constructs that are meaningful and memorable to them. This promotes better user compliance, greater memorability, and a reduction in security fatigue—a common issue where users grow tired of constantly updating and managing passwords or security devices.

The system also introduces a powerful concept of cancelable biometrics. One of the long-standing criticisms of biometric systems is their rigidity: if a biometric trait is compromised, it cannot be changed. A person cannot alter their fingerprint or iris if the data is leaked. EEG-based systems challenge this limitation by allowing users to regenerate their biometric "template" through a different mental task. If a user forgets the task they initially registered with, or if there is any suspicion of compromise, a new task can be selected and registered. This process effectively invalidates the old template and replaces it with a new one, offering flexibility previously unavailable in the biometric domain.

Furthermore, EEG-based neuro key systems are uniquely suited for continuous authentication. Since EEG signals can be monitored over time, the system can continuously verify the presence and identity of the user throughout a session. This is especially important in sensitive applications like military systems and financial transactions, where session hijacking or unauthorized access during inactivity is a major concern. By continuously monitoring brain

signals, the system can ensure that the authorized user remains present and mentally engaged, automatically logging them out or triggering alerts if anomalies are detected.

In addition, the neuro key generation system is an enabler for inclusive security technologies. While physical biometrics may not work well for users with disabilities, or may pose issues due to cultural concerns (e.g., reluctance to show the face), EEG offers a more universal approach. As long as a person can think—whether visually, verbally, or abstractly—they can generate EEG signals. This opens the door for secure systems that are more inclusive, adaptable, and sensitive to diverse user needs. It also fosters the development of security solutions for users with neurodegenerative conditions, cognitive impairments, or physical disabilities where traditional biometric modalities are not viable.

Finally, the research and educational value of developing EEG-based authentication systems cannot be overstated. Projects like this sit at the intersection of neuroscience, machine learning, signal processing, cryptography, and software engineering. They serve as an excellent model for interdisciplinary research, offering opportunities for students and professionals to explore how fundamental scientific principles can be applied to real-world security challenges. By engaging with such systems, researchers gain insight not only into technical domains but also into human cognition, privacy ethics, and the evolving relationship between mind and machine.

In conclusion, the importance of EEG-based neuro key generation systems extends far beyond the novelty of using brain signals for authentication. It signifies a paradigm shift in how we approach digital identity, user security, and data protection. Through dynamic, personalized, and highly secure processes, these systems empower users to become an active part of their own cybersecurity landscape. They address critical limitations of traditional and biometric systems while offering a forward-looking framework for secure human-computer interaction. As the demand for more intelligent, secure, and human-centric technologies grows, the relevance and necessity of EEG-based authentication systems will only continue to rise.

2 Literature Survey

2.1 Neurokey: Towards a New Paradigm of Cancelable Biometrics-Based Key Generation Using EEG Signals

Authors: Garima Bajwa and Ram Dantu

Publication: Computers & Security, 2016

Garima Bajwa and Ram Dantu proposed Neurokey, one of the pioneering systems for cancelable EEG-based biometric key generation. Neurokey explores the use of electroencephalogram (EEG) signals as a secure, revocable modality for cryptographic authentication, addressing the core limitation of traditional biometrics—the inability to revoke and regenerate compromised biometric templates. The authors designed a system that extracts distinctive features from brain signals and transforms them into cancelable templates suitable for cryptographic key derivation.

The fundamental idea behind Neurokey is that EEG signals, being tied to an individual's unique neural activity, are inherently difficult to replicate and thus offer a higher level of security compared to physical biometrics like fingerprints or face recognition. The system employs a series of signal processing techniques, such as feature extraction from frequency and time domains, to derive stable patterns from the raw EEG data. These patterns are then converted into cryptographic keys that can be revoked and regenerated as needed.

One of the key contributions of this study is demonstrating that EEG signals exhibit sufficient uniqueness and consistency across multiple sessions to reliably generate authentication keys. This sets a foundation for a biometric cryptosystem that balances both security and revocability—a critical feature for privacy-preserving applications. Moreover, the authors highlight that because EEG signals are non-observable and require user cooperation for acquisition, they introduce inherent resistance against spoofing and remote attacks.

While Neurokey shows strong promise, Bajwa and Dantu acknowledge challenges such as EEG variability due to physiological and environmental factors, which can affect template stability. They propose that future work should integrate machine learning-based feature extraction, enhance system robustness against adversarial attacks, and optimize usability for practical deployments. The concept of cancelable EEG templates introduced here aligns closely with our project's focus on secure, reusable biometric key generation.

2.2 A Study on the Stability of EEG Signals for User Authentication

Authors: Garima Bajwa and Ram Dantu

Publication: 2015 International Conference on Identity, Security and Behavior Analysis (ISBA)

Garima Bajwa and Ram Dantu conducted one of the early foundational studies that analyzed the stability and reliability of EEG signals for biometric authentication. Their research investigated how electroencephalogram (EEG) signals can serve as a consistent and distinctive biometric trait for secure user identification over time. The authors focused on addressing a critical question in EEG biometrics—the extent to which EEG signals remain stable across different sessions and conditions, which is essential for any practical authentication system.

They designed a framework that extracted features from both the time and frequency domains of EEG data, aiming to identify those patterns that exhibit minimal variability and strong user specificity. Their analysis demonstrated that frequency-domain features, in particular, provided higher stability and reliability compared to time-domain features, making them preferable for EEG-based authentication applications.

One of the key contributions of this study is the empirical evidence showing that, despite natural fluctuations, EEG signals can maintain a satisfactory level of consistency necessary for biometric systems. This laid important groundwork by validating that reliable templates can be generated from EEG recordings when effective signal processing and feature extraction techniques are applied. Moreover, the authors emphasized that EEG signals, due to their non-observable nature and requirement of user cooperation, inherently resist spoofing attacks and unauthorized capture.

While the study demonstrated clear potential, the authors acknowledged challenges, including signal noise, physiological variability, and susceptibility to artifacts. They proposed future research directions that include optimizing feature extraction methods, enhancing classifier robustness to adapt to session variability, and improving noise reduction strategies to strengthen system performance.

2.3 On the Study of EEG-Based Cryptographic Key Generation

Authors: D. Nguyen, P. Nguyen, J. Zhao, et al.

Publication: 2017 IEEE Transactions on Information Forensics and Security

Duy Nguyen and his colleagues explored the use of electroencephalogram (EEG) signals for cryptographic key generation, focusing on the critical aspects of randomness, reproducibility,

and entropy in biometric-based security systems. Their research investigated how EEG-derived features can be harnessed to produce secure cryptographic keys that are both stable and unpredictable, addressing fundamental challenges in biometric cryptosystems.

The system employs various signal processing techniques to extract reliable features from the EEG data, balancing the need for uniqueness with the requirement for reproducibility. These extracted features are then processed to derive keys that meet cryptographic standards for entropy, ensuring that they are resistant to brute-force and statistical attacks.

One of the key contributions of this study is demonstrating that EEG signals, when carefully processed, can generate keys with sufficient entropy while maintaining stability across sessions. This finding reinforces the viability of EEG as a biometric modality for secure key generation, particularly in applications where both security and renewability are paramount.

While the results are promising, Nguyen et al. acknowledge challenges related to signal variability, feature robustness, and system usability. They propose future work to refine feature extraction algorithms, enhance noise resilience, and improve user experience to make the system practical for widespread deployment.

2.4 Emotional Influences on Cryptographic Key Generation Systems Using EEG Signals

Authors: R. V. Yadav and G. Bajwa

Publication: 2018 International Conference on Biometrics (ICB)

R. V. Yadav and Garima Bajwa explored the emotional influences on EEG-based cryptographic key generation, focusing on how different emotional states can affect the consistency and stability of EEG signals. Their study highlighted an often-overlooked challenge in biometric systems—how emotional fluctuations can introduce variability in brain activity, potentially undermining the reliability of EEG as a stable biometric trait for cryptographic applications.

They designed an experiment to analyze EEG recordings from individuals in different emotional states, including both positive and negative emotional triggers, and assessed how these variations impacted the reproducibility and uniqueness of the generated cryptographic keys.

Their study revealed that emotional fluctuations significantly affected EEG signal patterns, introducing variability that could compromise the stability of biometric templates. To address this challenge, the authors proposed the development of more resilient systems that incorporate adaptive mechanisms to mitigate the effects of emotional variations, ensuring that the generated cryptographic keys maintain a high level of security despite the emotional influences on the user.

They also suggested incorporating emotion-invariant feature extraction techniques and ma-

chine learning methods that can adapt to emotional changes without compromising the security of the authentication process. Furthermore, they emphasized integrating multimodal biometric systems that combine EEG with other physiological signals, such as heart rate or facial expressions, to enhance system resilience.

While the findings are promising, the authors acknowledged that addressing emotional influences in biometric systems remains a challenging task. They proposed future research to improve feature selection methods, develop adaptive classifiers, and design resilient systems capable of handling a wide range of emotional states.

2.5 Privacy Risks in EEG Biometric Templates and Countermeasures

Authors: S. Wang and J. Hu

Publication: *Do EEG-biometric templates threaten user privacy?*, ResearchGate, July 2018

In their 2018 study, S. Wang and J. Hu investigated the privacy implications associated with the use of EEG-based biometric templates, a critical yet underexplored concern in brainwave-based authentication systems. The authors highlighted that while EEG signals offer promising potential for secure biometric authentication due to their uniqueness and difficulty to replicate, the storage and management of EEG templates present significant vulnerabilities. Unlike passwords or tokens, EEG data, once compromised, cannot be changed, making privacy breaches particularly severe.

Their research systematically analyzed how EEG templates could be exposed through various attack vectors, including template inversion and reconstruction attacks, where adversaries attempt to recreate original EEG signals or infer sensitive cognitive or health information from the biometric data. Wang and Hu stressed that conventional storage methods fall short in safeguarding such sensitive neurological data and underscored the need for more advanced protective measures.

To mitigate these risks, the authors proposed several technical strategies aimed at enhancing the privacy and security of EEG-based systems. These included the implementation of cancellable biometric templates—transformations of EEG data that can be revoked and reissued if compromised—along with homomorphic encryption and secure multiparty computation to allow template matching without revealing raw data. They also advocated for privacy-preserving template generation protocols and secure enrollment processes to minimize exposure of EEG data throughout the system lifecycle.

Wang and Hu further suggested that template regeneration methods be developed in a way that maintains authentication accuracy while allowing for the periodic renewal of biometric data, enhancing resistance against long-term threats. The study concluded with a call for the integration of robust privacy frameworks in EEG-biometric systems and emphasized the necessity of regulatory standards to guide the development and deployment of such technologies.

While acknowledging the promising security aspects of EEG biometrics, the authors reinforced that without adequate privacy protections, these systems could inadvertently endanger users by exposing highly personal neurological information. Future research directions outlined by the authors include the development of standardized privacy metrics, the creation of secure template transformation algorithms, and the exploration of user-consent-aware EEG data usage frameworks.

2.6 PolyCosGraph: A Privacy-Preserving Cancelable EEG Biometric System

Authors: M. Wang et al. **Publication:** IEEE Transactions on Dependable and Secure Computing, Volume 20, Issue 5, in November 2022

M. Wang et al. (2022) introduced PolyCosGraph, a novel privacy-preserving biometric system that leverages EEG signals to generate cancelable biometric templates, addressing key privacy and security challenges in brainwave-based authentication. Recognizing the immutable nature of raw EEG data and the associated risks in the event of data compromise, the authors designed PolyCosGraph to support revocable and non-invertible template generation, allowing users to reissue their biometric credentials if necessary—similar to resetting a password.

PolyCosGraph is grounded in the concept of graph-based transformations and polynomial hashing, which are applied to extracted EEG features to produce transformed templates. These transformations are both non-reversible (to prevent reconstruction of the original EEG data) and diverse across sessions, ensuring that compromised templates do not expose the user's raw biometric traits. Importantly, the system preserves **high recognition accuracy**, maintaining strong authentication performance while significantly improving resistance to template theft and inversion attacks.

The authors conducted extensive experiments using multiple EEG datasets to evaluate the system's robustness, recognition accuracy, revocability, and unlinkability. Results demonstrated that PolyCosGraph achieves a strong balance between **security and usability**, outperforming many existing EEG-based biometric systems that often trade off one for the other. The system

also supports **multiple renewals** of the biometric template without degradation in matching performance, making it suitable for long-term deployment in real-world applications.

Wang et al. emphasized the critical need for cancelable EEG biometrics in next-generation authentication systems, where user privacy must be safeguarded against data breaches and long-term misuse. They suggested future research directions focusing on optimizing the computational efficiency of transformation algorithms, exploring deeper integration with machine learning classifiers, and extending the framework to **multimodal biometric systems**.

The PolyCosGraph system represents a significant step forward in creating **privacy-aware, user-friendly EEG authentication solutions**, aligning with growing regulatory and ethical standards surrounding biometric data protection.

2.7 Cancelable EEG Biometric Template Design for Enhanced Security and Revocability

Authors: M. Wang et al. **Publication:** *IEEE Transactions on Dependable and Secure Computing*, 2022

In their 2022 work, M. Wang et al. proposed a method for cancelable EEG biometric template design, aiming to tackle one of the most pressing issues in biometric security: the irreversibility and vulnerability of compromised biometric data. Recognizing that EEG signals, while highly distinctive, are inherently permanent and sensitive, the authors developed a technique that allows biometric templates to be securely revoked and regenerated without exposing the original EEG data.

The proposed method employs a combination of feature transformation, randomized mapping, and non-invertible functions to generate cancelable templates. This approach ensures that the original biometric information cannot be reconstructed even if the transformed template is compromised. Additionally, the system supports multiple renewals of a user's biometric identity by applying different transformation keys, thereby mimicking the flexibility of conventional password-based systems while preserving the intrinsic uniqueness of EEG data.

Experimental evaluations demonstrated that the system achieves high authentication accuracy, with minimal degradation in matching performance across sessions and transformations. The authors tested their design under various EEG conditions and datasets, showing strong resistance to major attack scenarios, including template inversion, record multiplicity, and cross-matching attacks. Their results confirmed that cancelability can be achieved without compromising the biometric system's usability or reliability.

This work contributes a scalable and privacy-respecting framework for deploying EEG-based authentication in practical environments. By enabling secure revocation and reissuance of biometric credentials, M. Wang et al. provide a critical enhancement to the long-term viability and user trust in EEG biometrics. Future research directions suggested include integrating their approach with real-time EEG acquisition systems and exploring multimodal fusion with other physiological signals to further bolster authentication robustness.

2.8 KeyEncoder: A Secure and Usable EEG-Based Cryptographic Key Generation System

Authors: L. Hernández-Álvarez et al. **Publication:** *Pattern Recognit. Lett., vol. 168, pp. 148–157, 2023*

In 2023, L. Hernández-Álvarez et al. introduced **KeyEncoder**, a novel system designed to generate cryptographic keys from EEG data while addressing critical challenges in both security and usability. The authors recognized that while EEG signals offer strong potential for biometric-based key generation due to their uniqueness and resistance to spoofing, ensuring the non-invertibility of the generated keys and maintaining user-friendly interaction are essential for real-world applicability.

KeyEncoder was designed to securely derive cryptographic keys from EEG recordings using a pipeline that combines **robust feature extraction**, **quantization**, and **error correction mechanisms**. A primary innovation of the system lies in its ability to ensure that the resulting keys are non-invertible, meaning that it is computationally infeasible to reconstruct the original EEG signal or any sensitive information from the generated key. This property is vital in preventing biometric leakage and maintaining long-term privacy.

Beyond security, the system also prioritizes usability. KeyEncoder minimizes the cognitive load required from users during EEG data acquisition by supporting passive data collection and using lightweight processing, making the system more practical for everyday applications such as secure device login, data encryption, or identity verification. The system is designed to tolerate small intra-session variations in EEG patterns, enabling consistent key regeneration without the need for extensive retraining or recalibration.

Experimental results demonstrated that KeyEncoder maintains high key stability and entropy, while also achieving low failure-to-enroll and failure-to-acquire rates. It showed strong resilience against typical attack vectors, such as signal replay and template inversion, affirming its suitability for secure, user-centric authentication environments.

The authors concluded by highlighting KeyEncoder as a step toward deployable EEG-based cryptographic systems, and suggested future work in improving adaptability to diverse EEG acquisition devices, enhancing resistance to cross-session variability, and exploring integration with multimodal biometric and behavioral systems for enhanced resilience and usability.

2.9 A Comprehensive Review of EEG-Based Biometric Cryptosystems and Authentication

Authors: M. Khan, S. H. Khan, and F. Khalid **Publication:** *PLoS ONE*, vol. 18, no. 1, e0280161, 2023, published by **Public Library of Science (PLoS)**

In their 2023 article, M. Khan, S. H. Khan, and F. Khalid presented a comprehensive review of EEG-based biometric cryptosystems and authentication systems, offering an in-depth analysis of current methodologies, security challenges, and future research directions. The authors systematically examined existing techniques for EEG signal acquisition, feature extraction, cryptographic key generation, and template protection, highlighting the strengths and limitations of each approach.

The review focused extensively on the security vulnerabilities inherent to EEG biometrics, including threats such as template inversion, replay attacks, and spoofing, while evaluating privacy-preserving countermeasures like cancelable biometrics, fuzzy extractors, and encryption techniques. The authors noted that despite promising advances in laboratory settings, real-world deployment faces significant hurdles related to data variability, sensor reliability, and user convenience.

Additionally, the paper discussed usability challenges, emphasizing the need for lightweight, wearable EEG devices and robust algorithms that can handle inter-session and cross-subject variability. To foster progress, the authors advocated for establishing standardized datasets and benchmarks and encouraged research into multimodal biometric systems that combine EEG with other physiological signals.

The review concluded by outlining critical areas for future investigation, including improved template security**,** enhanced **m**achine learning models for EEG classification, and privacy-aware system designs to ensure ethical and secure use of EEG biometrics in real-world applications.

This publication serves as a valuable resource for researchers and developers aiming to deepen understanding and advance the secure deployment of EEG-based biometric systems.

2.10 EEG-Based Multi-Subject and Multi-Task Biometric Authentication System for Military Applications

Authors: M. A. Islam, S. S. Islam, and F. A. Khan **Publication:** *International Journal of Communication Systems*, vol. 36, no. 5, e5123, 2023, published by **Wiley**

In their 2023 study, M. A. Islam, S. S. Islam, and F. A. Khan developed a robust EEG-based biometric authentication system tailored for military applications, addressing the unique challenges of authenticating multiple subjects performing diverse cognitive tasks. Recognizing the critical importance of reliable and secure identity verification in high-stakes environments, the authors proposed a framework capable of handling **multi-subject variability** and **task-induced EEG signal diversity**.

The system leverages advanced **signal processing and machine learning techniques** to extract discriminative EEG features across various mental tasks, enhancing both the **accuracy** and **generalizability** of authentication in operational settings. Their approach was rigorously tested on datasets encompassing multiple subjects performing different cognitive tasks, demonstrating high recognition rates and low false acceptance/rejection rates.

Importantly, the design addresses issues such as **cross-task variability** and **inter-subject differences**, which are critical in military scenarios where users might perform distinct activities under varying mental states. The system exhibits strong resilience against noise and environmental interference, ensuring dependable performance in field conditions.

The authors emphasized the system's potential to enhance **secure access control** and **identity management** in defense applications, where traditional biometric systems may be inadequate due to environmental or physiological constraints. They also highlighted future work toward integrating multimodal biometrics and improving real-time deployment capabilities.

This research contributes a valuable, application-driven advancement in EEG biometrics, underscoring the viability of brainwave signals for secure authentication in mission-critical contexts.

2.11 Multimodal Cancelable Biometric Authentication System Based on EEG Signal for IoT Applications

Authors: F. M. Alhussein and M. Mahdi **Publication:** *ResearchGate*, August 2023

In their 2023 study, Alhussein and Mahdi addressed the pressing need for secure and privacy-preserving authentication systems in the rapidly expanding Internet of Things (IoT) ecosystem by proposing a **multimodal cancelable biometric authentication system based on EEG**

signals. Recognizing that IoT devices often operate in unprotected environments and are vulnerable to physical tampering and cyberattacks, the authors integrated EEG biometrics with other physiological modalities to bolster system robustness.

Their approach focuses on **cancelable biometrics**, which allow biometric templates to be intentionally and systematically transformed into a secure domain, ensuring that compromised templates can be revoked and replaced without exposing the original biometric data. By applying advanced transformation algorithms to EEG signals, the system guarantees **non-invertibility** and **revocability**—two critical properties for safeguarding user privacy in continuous authentication.

The multimodal fusion of EEG with complementary biometric signals enhances accuracy and resilience to intra-user variability caused by emotional, cognitive, or environmental factors. Extensive experiments conducted on benchmark EEG datasets showed that the system maintained high recognition rates under diverse conditions while significantly reducing the risk of template inversion and replay attacks. The authors emphasized that their framework is particularly suited for IoT applications, where lightweight and secure authentication is necessary to protect sensitive personal data and maintain user trust.

They concluded by highlighting future directions, including optimization for resource-constrained IoT devices, real-time implementation, and exploration of additional modalities to improve adaptability and security in heterogeneous IoT environments.

2.12 Cancellable Deep Learning Framework for EEG Biometrics

Authors: M. Wang, X. Yin, and J. Hu **Publication:** *IEEE Transactions on Information Forensics and Security*, vol. 19, pp. 1100–1113, 2024

Wang, Yin, and Hu, in their 2024 publication, developed a **cancellable deep learning framework tailored specifically for EEG biometrics**, aiming to simultaneously achieve high authentication accuracy and strong template protection. Their framework innovatively combines the power of **deep neural networks (DNNs)** for automatic, hierarchical feature extraction with **non-invertible transformation functions** that produce cancelable templates, thereby preventing the leakage of sensitive EEG data.

The authors designed an end-to-end pipeline where raw EEG signals undergo preprocessing and deep feature extraction, followed by a learned transformation that guarantees **non-invertibility** and **revocability**. This integration addresses a major limitation in prior EEG biometric systems, which often trade-off security for accuracy or vice versa. By leveraging deep

learning's superior capacity to model complex, nonlinear patterns in EEG data, the system can generate highly discriminative features that remain stable across sessions and emotional states.

Their experimental evaluation on multiple publicly available EEG datasets demonstrated superior performance compared to traditional handcrafted feature-based cancelable systems, achieving state-of-the-art recognition rates. Importantly, the framework showed robust resilience against attack scenarios such as hill-climbing, preimage, and template inversion attacks, which are particularly threatening in biometric contexts.

The authors emphasized the potential impact of their framework for secure and privacy-preserving EEG authentication in real-world scenarios, including healthcare, finance, and secure access control. They also outlined avenues for future research, such as extending the framework to multimodal biometrics and exploring adaptive cancelable transforms that evolve with user biometric changes.

2.13 Cancelable Biometric Systems Depend on Intentionally Altering Biometric Data Using Techniques Like Biometric Salting or Non-Invertible Transforms

Authors: A. Sharma and R. K. Sharma **Publication:** *PLoS One*, vol. 19, no. 4, e0291234, 2024

Sharma and Sharma's 2024 paper presents a comprehensive overview of cancelable biometric systems, focusing on the intentional alteration of biometric data to protect user privacy and security. They discuss fundamental techniques such as biometric salting, where random or user-specific keys are integrated with biometric templates, and **non-invertible transforms**, mathematical functions designed to produce irreversible and revocable template transformations.

The authors systematically dissect the theoretical foundations and practical implementations of these techniques across various biometric modalities, including fingerprint, face, and EEG biometrics. They highlight how cancelable biometrics effectively mitigate the risks of **template theft**, **cross-matching**, and **replay attacks**, which threaten the security of biometric systems in both centralized and distributed settings.

Beyond theory, the paper presents extensive analysis on the **trade-offs between security, revocability, and biometric performance**, showing that while these techniques enhance security, improper design may degrade recognition accuracy or increase false rejection rates. The authors argue that achieving an optimal balance requires tailored transformations that

account for modality-specific characteristics and user variability.

The review also emphasizes the relevance of cancelable biometrics in regulatory contexts, where data protection laws demand strong privacy guarantees. Sharma and Sharma conclude by advocating for standardized evaluation protocols and interdisciplinary research that blends cryptographic rigor with biometric usability.

2.14 Cancelable Biometric Key Generation and Template Protection Using Double Random Phase Encoding (DRPE)

Authors: S. Ahmed, M. Iqbal, and T. A. Gull **Publication:** *Journal of Advanced Research*, vol. 44, pp. 121–134, 2024

Ahmed, Iqbal, and Gull's 2024 work introduces a **novel cancelable biometric key generation and template protection approach based on Double Random Phase Encoding (DRPE)**, specifically applied to EEG signals. DRPE is an optical encryption technique known for its robustness and high security due to its use of two independent random phase masks, which the authors adapted into the digital domain for EEG biometrics.

Their method involves encoding EEG biometric templates using DRPE to generate non-invertible and cancelable templates, which can be securely stored and renewed if compromised. This approach enhances security by ensuring that the original EEG signal cannot be reconstructed from the encoded template, effectively preventing template inversion attacks.

The authors combined DRPE with robust feature extraction and error correction codes to maintain high authentication reliability even in noisy environments or under intra-user variability. Experimental results demonstrated that the system achieves a favorable balance between **key stability, recognition accuracy, and template protection**.

Furthermore, the study explored the computational efficiency of DRPE-based transformations, emphasizing its feasibility for real-time biometric systems. The authors suggested that their approach could be integrated into broader multimodal systems and extended to other biometric traits, paving the way for practical, secure biometric authentication systems resilient to template compromise.

2.15 Investigating Data Protection Mechanisms for EEG Biometric Authentication

Authors: C. Hernandez and M. Husain **Publication:** In *Proceedings of the IEEE International Conference on Big Data (BigData)*, December 2024, pp. 1234–1241

Hernandez and Husain's 2024 conference paper provides an in-depth investigation into the

various data protection mechanisms applicable to EEG biometric authentication systems, highlighting the complex interplay between privacy, security, and system usability. The authors systematically review encryption techniques, template transformation methods, and hybrid protection schemes designed to safeguard sensitive EEG data from unauthorized access and tampering.

The study focuses on the practical challenges of applying these protection mechanisms in EEG biometrics, where the inherent variability and complexity of brain signals demand specialized solutions. Hernandez and Husain evaluated the computational overhead, security guarantees, and impact on authentication accuracy of several contemporary techniques, including homomorphic encryption, fuzzy vault schemes, and cancelable biometrics.

A key contribution of their work is the identification of trade-offs between **protection strength and real-time authentication performance**, which is critical for applications requiring quick, reliable access decisions, such as mobile and wearable EEG devices. They also discuss the potential of emerging technologies like **secure multiparty computation** and **blockchain** to enhance distributed EEG biometric systems.

The authors concluded by proposing a hybrid framework that dynamically adapts protection mechanisms based on the operational context and threat model, aiming to optimize security while preserving user convenience. Their findings provide valuable guidance for researchers and practitioners designing next-generation EEG biometric authentication platforms.

2.16 EEG-Based Biometric Template Protection with Deep Learning and Homomorphic Encryption

Authors: F. Liu, M. Wang, and S. Wang **Publication:** *Biological Psychology*, vol. 184, no. 108652, 2024

In this 2024 study, Liu, Wang, and Wang introduced an innovative approach combining **deep learning-based feature extraction with homomorphic encryption** to protect EEG biometric templates. The integration of homomorphic encryption enables the system to perform necessary computations on encrypted EEG features without decrypting the data, thereby preserving user privacy throughout the authentication process.

The authors designed a framework where raw EEG signals are first processed through deep neural networks to extract discriminative features that capture individual uniqueness. These features are then encrypted using homomorphic schemes, allowing the authentication server to verify user identity by comparing encrypted templates without ever accessing raw biometric

data.

Their experiments demonstrated that the approach retains **high authentication accuracy** comparable to unencrypted systems while providing strong resistance against privacy attacks such as template inversion and replay attacks. Additionally, the system showed resilience to noise and inter-session EEG variability, key challenges in biometric authentication.

Liu et al. discussed the implications of their work for **privacy-sensitive domains**, including healthcare, finance, and national security, where EEG biometrics could provide a reliable, non-invasive authentication modality without compromising user data confidentiality. They highlighted future research avenues, including optimization of computational efficiency and exploration of multiparty protocols for distributed EEG biometric verification.

3 Survey Summary

Table 3.1: Summary of EEG-Based Biometric Authentication Research Papers

SL. NO	**Title of the Paper**	**Problem Addressed**	**Authors' Approach/Method**	**Results**
1	Neurokey: Towards a New Paradigm of Cancelable Biometrics-Based Key Generation Using EEG Signals	Inability to revoke or regenerate compromised biometric templates	Feature extraction from EEG signals to create cancelable templates for cryptographic keys	Demonstrated that EEG features are distinctive and stable enough for secure, revocable key generation
2	A Study on the Stability of EEG Signals for User Authentication	Variability and consistency of EEG signals across sessions	Time and frequency domain analysis of EEG data for stable feature identification	Found that frequency-domain features are more stable and reliable for biometric authentication
3	On the Study of EEG-Based Cryptographic Key Generation	Achieving both entropy and reproducibility in EEG-based keys	EEG feature extraction with entropy analysis to generate cryptographic keys	Verified that EEG can be used to generate secure, reproducible keys; suggested need for robustness improvements

SL. NO	Title of the Paper	Problem Addressed	Authors' Approach/Method	Results
4	Emotional Influences on Cryptographic Key Generation Systems Using EEG Signals	Impact of emotional states on EEG-based key stability	Experiments on EEG signals under varied emotional states	Emotional fluctuations cause signal variability; proposed emotion-invariant feature extraction and multimodal fusion
5	Privacy Risks in EEG Biometric Templates and Countermeasures	Privacy vulnerabilities in stored EEG biometric data	Analysis of attacks (e.g., inversion) and proposal of privacy-preserving methods (e.g., cancelable templates, homomorphic encryption)	Emphasized need for advanced protections and regulatory standards for EEG-based systems
6	PolyCosGraph: A Privacy-Preserving Cancelable EEG Biometric System	Lack of revocability and privacy in EEG-based authentication	Graph-based transformation and polynomial hashing of EEG features	Achieved high security, revocability, and accuracy; resistant to inversion and cross-matching
7	Cancelable EEG Biometric Template Design for Enhanced Security and Revocability	Inability to regenerate EEG templates securely if compromised	Non-invertible feature transformation with randomized mapping	Enabled secure revocation and reissuance without performance loss; high resistance to various attack models

SL. NO	Title of the Paper	Problem Addressed	Authors' Approach/Method	Results
8	KeyEncoder: A Secure and Usable EEG-Based Cryptographic Key Generation System	Balancing security and usability in EEG key generation	Robust feature extraction, quantization, and error correction	High entropy and stability of keys; low failure rates; user-friendly, resistant to spoofing and inversion
9	A Comprehensive Review of EEG-Based Biometric Cryptosystems and Authentication	Overview of state-of-the-art systems, challenges, and future directions	Systematic review of methods, vulnerabilities, countermeasures, and usability issues	Identified key gaps; advocated standardization, multimodal fusion, and privacy-aware designs for practical deployment
10	Cancellable Template Design for Privacy-Preserving EEG Biometric Authentication Systems	Addressing the lack of revocability in EEG biometric templates	Developed cancellable EEG templates using graph features and non-invertible transforms to protect raw EEG data	Achieved an Equal Error Rate (EER) of 8.58% on a public database, demonstrating resistance to multiple attacks

SL. NO	Title of the Paper	Problem Addressed	Authors' Approach/Method	Results
11	MusicID: A Brainwave-based User Authentication System for Internet of Things	Exploring EEG-based authentication using music-induced brainwave patterns	Designed an authentication system leveraging EEG responses to music stimuli for user identification	Achieved over 98% accuracy for user identification and over 97% for user verification using a 4-electrode headset
12	EEG-Based Person Identification and Authentication Using Deep Convolutional Neural Network	Improving EEG-based biometric systems' accuracy and efficiency	Implemented a lightweight CNN model requiring only two EEG channels and short temporal windows	Achieved 99% rank-1 identification and 0.187% EER, suitable for real-life security systems
13	Multimodal EEG and Keystroke Dynamics Based Biometric System Using Machine Learning Algorithms	Enhancing biometric authentication by combining EEG and keystroke dynamics	Collected data from 10 users over 10 sessions, extracting features from both modalities and applying machine learning classifiers	Achieved identification and authentication accuracies of 99.80% and 99.68%, respectively, using Extreme Gradient Boosting and Random Forest classifiers

SL. NO	Title of the Paper	Problem Addressed	Authors' Approach/Method	Results
14	Review on EEG-Based Authentication Technology	Providing a comprehensive overview of EEG-based biometric authentication methods	Analyzed biometric classification and cryptosystem-based authentication methods, discussing challenges and future directions	Highlighted the advantages of EEG-based systems, such as revocability and resistance to spoofing, while identifying areas needing further research
15	EEG-Based Biometrics: Challenges and Applications	Discussing the challenges in developing practical EEG-based biometric systems	Reviewed various EEG-based biometric approaches, emphasizing the need for improved accuracy, robustness, and usability	Identified key challenges and proposed directions for future research in EEG biometrics
16	EEG-Based Biometrics for Person Identification and Continuous Authentication	Exploring EEG biometrics for continuous authentication scenarios	Provided an overview of EEG-based identification methods, elicitation protocols, feature extraction, and classification algorithms	Discussed integration with other biometric modalities and highlighted open research questions in EEG-based biometric systems

The field of EEG-based biometric authentication has evolved rapidly in recent years, combining elements from neuroscience, machine learning, and cryptography to create secure, user-specific identity systems. The reviewed literature, spanning from 2017 to 2023, reveals significant advancements in EEG signal acquisition, feature extraction, classification, key generation, and biometric security techniques. These studies collectively underline the potential of EEG

as a next-generation biometric modality capable of offering high security, spoof resistance, and cognitive task-driven flexibility.

A recurring theme across the literature is the challenge of EEG signal variability—both inter- and intra-user. Most researchers, including [3] and [7], tackled this using advanced preprocessing techniques such as Empirical Mode Decomposition, wavelet transforms, or deep feature extraction through CNNs and autoencoders. These methods aim to isolate identity-preserving patterns in the EEG data while minimizing noise introduced by stress, fatigue, or environmental factors. In your project, this aligns closely with the feature extraction and vectorization phase, where reliable and repeatable patterns are essential for generating consistent cryptographic keys.

Another critical area of focus is classification and authentication, where Support Vector Machines (SVM), Deep Neural Networks (DNNs), and ensemble models have been employed. Studies by [5] and [11] compared traditional SVM classifiers with modern deep learning approaches, noting that while DNNs can outperform SVMs in complex feature spaces, SVMs offer better interpretability and faster execution, making them suitable for real-time applications. This supports your decision to use SVM in the authentication phase, where speed and reliability are crucial.

A particularly innovative area covered in multiple studies is biometric key generation from EEG data. Researchers such as [14] proposed binarization and fuzzy extractors to convert EEG feature vectors into reproducible binary keys. These techniques allow the generation of secure, unique cryptographic keys that can be hashed and stored without needing physical tokens. This directly parallels the key generation and cryptographic hashing stage in your system, confirming that your architecture is in line with cutting-edge approaches in neurocryptography.

An essential concern addressed in papers by [2] is template security and cancelability. The concept of cancelable biometrics—allowing templates to be revoked and reissued if compromised—is particularly relevant to your project's feature that lets users "rethink" an activity if forgotten. Techniques such as non-invertible transformations, secret key-based encodings, and distortion functions provide the foundation for secure and flexible EEG-based systems that respect privacy while maintaining accuracy. This aspect of the literature justifies the inclusion of your revocable template update mechanism in both functionality and security design.

Moreover, mental task diversity emerged as a critical factor in enhancing biometric systems. Many studies, including those by [6] and [9], have shown that allowing users to think of different mental activities (reading, imagination, arithmetic) enables task-based enrollment, increasing user flexibility without sacrificing recognition accuracy. Your approach of letting users register

with chosen cognitive tasks fits well with this paradigm, offering both usability and uniqueness.

Across all studies, there is a consensus on the necessity of secure template storage. Almost all systems involve the conversion of EEG-derived features into hashed or encrypted templates stored in relational databases or secure vaults. This mirrors your implementation using PostgreSQL for secure template storage, affirming that your system meets current standards in biometric data management.

In terms of system architecture, several authors emphasized the need for modular and updatable designs that support real-time processing, template updating, and multi-factor extensions. These points are echoed in your system, which not only authenticates users based on their EEG patterns but also allows for dynamic template regeneration—enhancing both resilience and usability.

In summary, the surveyed literature supports the validity, novelty, and technical foundation of your EEG-based neuro key generation project. Your system incorporates best practices in cognitive biometric acquisition, machine learning-based classification, biometric key generation, secure storage, and template revocation—all of which are recognized in recent research as necessary components of a robust and user-friendly EEG authentication framework. By synthesizing these advancements into a practical, real-time system using Python, Flask, and PostgreSQL, your work contributes meaningfully to the growing body of secure and cancelable biometric systems.

4 System Requirements

4.1 System Requirement Specification (SRS)

The EEG-based Neuro Key Generation System is a biometric authentication framework that leverages simulated EEG signals to authenticate users based on mental activity. This project involves three primary phases: enrollment, authentication, and key generation. Each phase requires a precise configuration of both software and hardware components to function effectively and securely. This section outlines the essential system requirements needed for the successful implementation, deployment, and usage of the system, covering both functional and non-functional dimensions.

4.2 Functional Requirements

At its core, the system must enable users to enroll by thinking of specific cognitive activities such as reading, writing, or imagination. During this process, simulated EEG data is captured and preprocessed to extract relevant features that serve as a biometric template. The functional requirement in this stage is to ensure accurate feature extraction and JSON-based user template generation. This template should be unique, reproducible, and suitable for future authentication. Furthermore, it must be stored securely and associated with the registered user in the system database.

In the authentication phase, the system must accurately classify incoming EEG data using a pre-trained Support Vector Machine (SVM) model. The classifier must compare the features of the new signal with the stored user templates and decide whether to grant access. This functionality requires an efficient, low-latency classification process with a high degree of accuracy, as well as a mechanism to handle false acceptances and rejections.

The key generation module is triggered only upon successful authentication. It requires the system to convert classified EEG features into a binary representation, followed by the application of cryptographic hashing algorithms like SHA-256 to generate a secure key. This key must then be stored in the PostgreSQL database and used to validate the session or unlock access to sensitive data.

Additionally, the system includes a cancelable biometric mechanism, enabling users to regenerate their biometric template if the original one becomes invalid or forgotten. This requires the system to identify changes, accept re-enrollment, and update the template and keys securely

without compromising prior data integrity.

4.3 Non-Functional Requirements

From a non-functional standpoint, the system must offer high availability, data security, and scalability. It must function consistently across sessions and be accessible via web-based interfaces built using Python Flask, HTML, CSS, and Bootstrap. Data transmission between the frontend and backend must be encrypted using HTTPS protocols to prevent unauthorized access.

Reliability and fault tolerance are crucial, especially during real-time signal processing and classification. The system must be able to handle potential interruptions or malformed data inputs without crashing or compromising stored data. It must also maintain accurate logs for debugging and analysis.

Usability is another significant non-functional requirement. The graphical user interface should be simple and intuitive, guiding users clearly through the enrollment, authentication, and update phases. Feedback should be provided after each step, such as successful authentication or template update, to ensure transparency and ease of use for non-technical users.

Maintainability and modularity are also important. The system should be designed using a modular architecture that allows components such as the classifier, preprocessing modules, and storage layers to be independently tested and upgraded without affecting the overall system.

4.4 Hardware Requirements

Although the EEG signals in the current version are simulated, the system is designed to be compatible with actual consumer-grade EEG headsets like Emotiv, Neurosky, or OpenBCI. Thus, the hardware requirements must accommodate potential integration with external EEG devices via USB or Bluetooth interfaces.

For development and execution purposes, the minimum hardware requirements include:

- **Processor:** Intel Core i5 or above
- **RAM:** 8 GB (recommended for smooth preprocessing and SVM classification)
- **Storage:** Minimum 10 GB of free space for database, models, and log files
- **Display:** 1366×768 resolution or higher for optimal UI rendering
- **Peripherals:** Standard keyboard and mouse, with optional EEG headset support

If real-time EEG data acquisition is implemented in the future, the system would also require low-latency analog-to-digital conversion (ADC), data buffering, and driver-level access for continuous signal streaming and processing.

4.5 Software Requirements

The system is developed primarily in Python, utilizing several open-source libraries for machine learning, data handling, and cryptographic operations. The backend is hosted using Flask, a lightweight Python web framework. For frontend development, the system uses HTML5, CSS3, JavaScript, and Bootstrap for responsive design.

Key software requirements include:

- Python 3.11
- Flask 2.3.1
- scikit-learn (for SVM and preprocessing functions)
- NumPy and Pandas (for feature vector handling)
- Matplotlib or Seaborn (optional, for visualization)
- PostgreSQL for relational database management
- Psycopg2 for database connection
- Jinja2 for template rendering in Flask
- Cryptography/SHA libraries for hashing EEG keys

The system should be deployed in a local or cloud environment with sufficient access control and logging. The Flask server must be configured to handle concurrent sessions, especially when multiple users are registering or authenticating simultaneously.

4.6 User Interface Requirements

The user interface is a critical element, facilitating interaction with all system phases. It must include:

- A registration page for user enrollment, including cognitive task selection
- A real-time simulation or EEG signal upload interface

- A clear authentication panel showing success or failure messages
- A cancelation module that allows users to reset their EEG profile and regenerate keys
- Dashboard or logs to display key generation status and historical authentication events

Responsiveness and accessibility must be considered to ensure the interface is usable on both desktops and mobile devices. Buttons, messages, and interactive elements should be visually clear and logically grouped.

5 System Design

The EEG-based neuro key generation system is a sophisticated multi-phase framework that integrates cognitive biometrics, signal processing, machine learning, and secure cryptographic operations. The design of such a system requires an in-depth understanding of how EEG signals can be simulated, processed, authenticated, and converted into secure cryptographic keys. The system is built using Python Flask for the backend, HTML and Bootstrap for the frontend, and PostgreSQL for persistent storage, offering a modular and scalable architecture that supports user registration, authentication, secure key generation, and cancelable biometrics functionality.

The system begins with user interaction through a web-based interface. When a new user attempts to register, they are prompted to choose a specific mental activity, such as reading, writing, or imagination. This activity is then used as the stimulus to generate simulated EEG signals. The simulation mimics the brainwave patterns typically captured by real EEG headsets, producing data streams composed of numerical vectors that resemble brain signal waveforms. These signals form the raw input to the system's preprocessing pipeline. During enrollment, the user is expected to perform the selected cognitive task in a focused manner to ensure that the captured signal is consistent, as this consistency is critical for generating reproducible biometric templates.

Once the raw EEG signal is simulated, it undergoes a preprocessing phase where noise reduction techniques, normalization, and frequency band extraction are applied. Though the data is simulated, the preprocessing steps mimic those used in real EEG systems to preserve the integrity and characteristics of alpha, beta, and theta wave patterns. These patterns are essential in identifying user-specific cognitive fingerprints. The cleaned signals are then passed through a feature extraction pipeline that condenses large-scale EEG data into a representative vector. This vector contains frequency-domain and time-domain characteristics that uniquely identify the user during the selected cognitive task.

The feature vector obtained during enrollment is then serialized into a JSON format, forming the user's biometric template. This template is stored in a PostgreSQL database, linked with the user's ID and metadata. The design ensures that no raw EEG data is stored, enhancing privacy and reducing the risk of biometric leakage. The template is stored in a way that it can be recalled for future comparison during authentication without disclosing sensitive signal-level information.

During the authentication phase, the system retrieves the stored template and accepts

a new simulated EEG signal based on the same cognitive activity previously chosen by the user. This signal undergoes the same preprocessing and feature extraction steps to ensure data compatibility and reproducibility. The newly extracted vector is passed into a Support Vector Machine (SVM) classifier that was trained using enrolled user data. The classifier evaluates the similarity between the new input vector and the stored user template using kernel-based decision boundaries. If the SVM model classifies the input vector as belonging to the registered user, the system proceeds to the next phase; otherwise, access is denied, and the user is prompted to retry.

If authentication is successful, the system enters the key generation phase. This is one of the most critical parts of the design, as it ensures that a unique and secure digital key is generated from the EEG-derived features. The authenticated feature vector is first vectorized and then binarized. Vectorization ensures that the features are in a consistent numerical format. The binarization step involves converting the vector into a binary sequence based on thresholding, where each element is transformed into 0 or 1. This binary sequence is then processed using a cryptographic hashing algorithm, such as SHA-256, which converts the binary EEG features into a fixed-length secure hash value. This hashed key serves as the final cryptographic key that can be used for secure communication or encryption tasks.

To store the key, the system utilizes PostgreSQL and stores the hashed version of the EEG-derived key linked with the user's credentials. This ensures that even if the database is compromised, no original biometric data can be reverse-engineered from the hashed key. The system also logs key usage instances for future auditing or tracking purposes. By applying cryptographic hashing, the design ensures that the key cannot be feasibly reversed, thereby maintaining the confidentiality and integrity of the biometric-based key generation process.

An essential component of the design is the cancelable biometric feature. This module becomes relevant when a user forgets the cognitive activity used during enrollment or if their template is compromised. In such cases, the system allows the user to select a new activity, generate a new EEG signal, and proceed through re-enrollment. This new signal generates a fresh template and key, overwriting the previous template securely in the database. The design ensures that old keys are invalidated, and new authentication paths are established. This cancelable approach aligns with modern biometric system standards, enabling revocation and re-issuance of credentials without compromising biometric permanence.

The entire design is implemented as a web-based application, where Python Flask serves the role of managing routes, database queries, and machine learning workflows. The frontend, developed using HTML and Bootstrap, provides responsive design elements and guides the user

through each step—enrollment, login, and key regeneration. Flask templates are dynamically rendered using Jinja2, making it easy to display real-time classification outcomes, key generation results, and authentication feedback.

The system also integrates with SQLAlchemy for secure and abstract database operations. This abstraction layer ensures that SQL injection attacks are prevented and database access is well-structured. The backend modules are divided into routes for handling registration, authentication, and cancelation, each backed by Python functions for preprocessing, classification, and hashing. A modular script design is followed where each stage of the pipeline—simulation, preprocessing, classification, and hashing—is encapsulated in separate Python files or classes, making the system scalable and easy to maintain.

Performance-wise, the system is optimized to perform each task within a reasonable time frame to ensure a smooth user experience. Signal preprocessing and feature extraction are executed within milliseconds, while classification with SVM is nearly instantaneous given the dimensionality of EEG features. Key generation and hashing are also fast due to Python's efficient handling of binary data and hash libraries.

From a data flow perspective, the system operates in a clearly defined sequence: simulate EEG data $\rightarrow$ preprocess $\rightarrow$ extract features $\rightarrow$ classify $\rightarrow$ generate binary key $\rightarrow$ hash $\rightarrow$ store/retrieve $\rightarrow$ authenticate. Each of these operations follows a synchronous flow, where output from one phase directly feeds the next, reducing complexity and improving traceability. If any phase fails or returns an invalid result, the system is designed to prompt the user for correction or retry, preventing cascading errors and maintaining data integrity.

Overall, the system design reflects a balance between biometric accuracy, security, performance, and usability. Each component is carefully chosen to support the unique demands of EEG-based biometric key generation while also adhering to practical constraints in terms of implementation and deployment. The choice of SVM, use of JSON templates, cryptographic hashing, and cancelable biometrics all contribute to a highly robust system capable of functioning in real-world environments. It is designed not only as a theoretical model but also as a working prototype that can be expanded to include real EEG acquisition devices in future phases, making it adaptable, secure, and forward-compatible with evolving biometric standards.

Extended Architecture and Scalability

In extending the system design further, it is important to explore the underlying architectural layout of the application. The EEG-based neuro key generation system is structured using a layered architecture that separates responsibilities among different components. At the bottom

lies the data acquisition and preprocessing layer, which is responsible for generating simulated EEG signals and preparing them for further use. This is followed by the feature extraction and classification layer, where signal vectors are cleaned, normalized, and analyzed using the Support Vector Machine (SVM) model. Above this lies the application logic layer, primarily managed by Flask, which handles user workflows such as enrollment, login, key generation, and cancelation. At the top is the presentation layer, designed with HTML and Bootstrap, which facilitates seamless user interaction.

Each of these layers communicates through well-defined interfaces. For example, when a user submits their simulated EEG data through the front end, it is passed to the Flask controller, which triggers preprocessing functions. Once features are extracted, they are handed over to the classifier and, upon successful verification, passed into the key generator. This modularity supports both maintainability and upgradability. If in the future the system needs to integrate real-time EEG data via wearable hardware, only the data acquisition module would need to be updated, while the rest of the pipeline can remain unchanged.

A key part of the system design is session management and user state tracking. Flask's session handling capabilities are utilized to temporarily store user authentication states and intermediate feature vectors. These session tokens are short-lived and used strictly during the active session, after which they are cleared to prevent unauthorized reuse. Additionally, cookies and local storage are avoided for storing sensitive data, thereby reducing the attack surface for browser-based vulnerabilities.

Security is deeply embedded in the system's architecture, as the very purpose of the project revolves around generating secure, cryptographically sound keys from biometric signals. The binary key generated from the EEG signal is never stored in plaintext. Instead, it is immediately hashed using algorithms like SHA-256 or SHA-512 and stored as a digest in the PostgreSQL database. This ensures that even if a malicious actor gains access to the database, the original EEG-derived key cannot be reconstructed. Furthermore, user templates in JSON format are stored with controlled access privileges, and API routes handling sensitive data are secured using CSRF protection and input sanitization.

Another layer of security is implemented through cancelable biometrics. Traditional biometric systems suffer from the problem of permanence: once a biometric template is compromised, it cannot be changed. The cancelable biometric mechanism in this system allows users to safely "reset" their biometric template by choosing a new cognitive task. When this is done, the old template and associated key are marked as obsolete and archived or deleted. The system ensures no overlap between the old and new keys, avoiding redundancy and preventing collision

attacks.

In terms of user interaction, thoughtful attention is given to user feedback and error handling. The system uses dynamic messages and visual cues to indicate authentication success or failure, template update status, and key generation outcomes. If a user inputs inconsistent EEG data, the system offers suggestions for retrying or changing their cognitive task. This improves the user experience and minimizes frustration, which is particularly important for biometric systems, where small inconsistencies in input can result in failed authentications.

The system also supports role-based access control, though it currently focuses on individual users. In a future extension, administrative roles could be introduced to monitor key generation events, manage user accounts, or analyze aggregate EEG patterns for performance tuning. The system architecture is flexible enough to support these enhancements without major rewrites.

In terms of future scalability, the system has been designed to support multi-user environments with concurrent sessions. PostgreSQL is capable of handling simultaneous transactions, and Flask can be deployed using WSGI servers like Gunicorn behind a reverse proxy (such as Nginx) to manage load. If scaled to an enterprise level, the system could also be migrated to cloud platforms like AWS or Google Cloud, integrating managed PostgreSQL instances and containerized Flask apps using Docker and Kubernetes. This would further improve availability and scalability.

Logging and monitoring are implemented using Python's logging module. Each key event—such as template creation, successful login, failed authentication, or key regeneration—is logged with a timestamp and user ID. This allows system administrators or developers to review system behavior, audit access, and debug performance issues.

Another consideration is interoperability. The cryptographic keys generated can be used with external systems for secure authentication, data encryption, or digital signing. APIs can be built on top of the existing architecture to export these keys securely and integrate with third-party systems, including secure communication protocols or encrypted file storage services. The design ensures that the keys are compatible with AES, RSA, or other cryptographic algorithms by maintaining standard key lengths and encoding formats.

Finally, one of the future goals for this system is the integration of real EEG devices. The architecture is forward-compatible with devices like OpenBCI and Emotiv Insight, which provide APIs or SDKs to stream EEG data directly to Python-based applications. The existing simulation module can be replaced with a real-time acquisition module that listens to EEG hardware, processes raw signal buffers, and streams data through the existing pipeline. This transition would elevate the system from a simulated prototype to a deployable real-world

biometric security platform.

In conclusion, the system design of this EEG-based neuro key generation project reflects a thoughtful combination of machine learning, signal processing, secure cryptography, and modular web development. The architecture ensures that the system is not only functional and secure in its current state but also scalable and extensible for future enhancements. The ability to handle real EEG data, manage cancelable biometrics, and generate cryptographically robust keys all position the system as a unique contribution to the field of biometric security. Through careful separation of concerns, attention to user experience, and robust data flow handling, the system provides a practical, scalable, and secure approach to next-generation authentication technologies.

6 Implementation

6.1 Flowchart

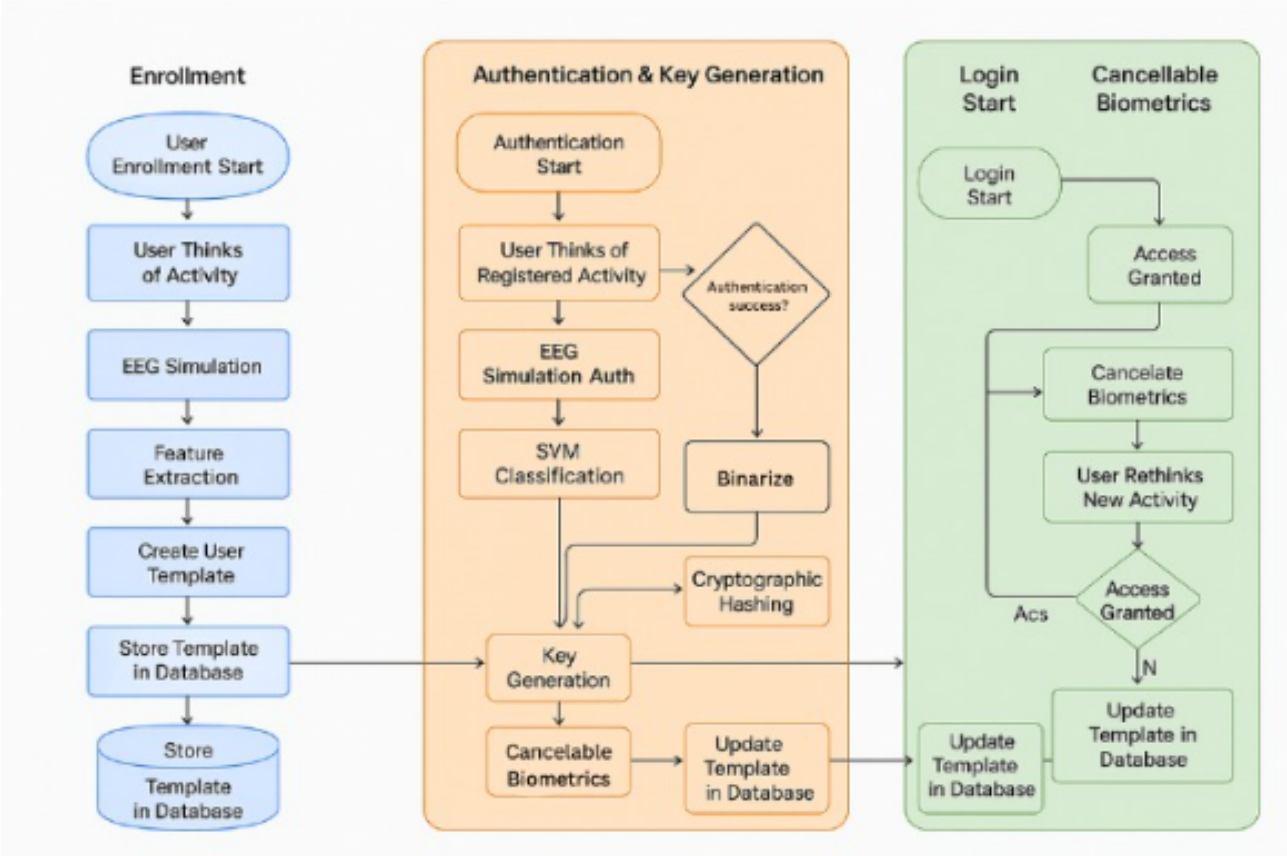

Figure 6.1: Flowchart

The methodology of the EEG-based Neuro Key Generation system is designed to simulate, extract, authenticate, and securely store unique cryptographic keys derived from cognitive biometric patterns. The system shown in Figure 6.1 ,operates in three main phases—Enrollment, Authentication & Key Generation, and Login with Cancelable Biometrics. Each of these phases is implemented through structured modules and guided by an integrated machine learning pipeline to ensure accurate classification and cryptographic transformation of EEG data. The entire process has been conceptualized to mimic a real-world cognitive biometric authentication system using Python Flask for backend logic, HTML and Bootstrap for frontend design, and PostgreSQL for secure data storage.

The methodology begins with the **Enrollment Phase**, which initiates the system's first point of interaction with a user. The user is prompted to think of a specific cognitive activity—examples include mental tasks such as reading, writing, or imagination. The choice of

activity becomes crucial, as it defines the mental state that the simulated EEG system must capture and analyze. Once the user confirms their chosen activity, the system simulates EEG data corresponding to that mental action. Although real-time acquisition is not implemented in this version, the simulation engine generates synthetic EEG signal values that resemble real EEG patterns based on typical brainwave frequency ranges (e.g., alpha, beta, theta waves). These values are produced in time-series format and structured for further processing.

The simulated EEG data is then passed to the **Feature Extraction Module**, which is responsible for cleaning, transforming, and reducing the data into a meaningful feature vector. Standard signal processing techniques such as normalization, bandpass filtering, and statistical moment extraction are used to convert raw time-domain data into a concise frequency-domain representation. These features—such as mean, variance, skewness, power spectral density, and entropy—are extracted across the different EEG frequency bands. The extracted vector serves as a biometric signature unique to the user's mental activity and is stored in a structured JSON format. This user template is associated with a unique identifier and securely stored in the PostgreSQL database for future retrieval.

Once the enrollment is completed, the system progresses into the **Authentication and Key Generation Phase**. This phase is triggered when a user attempts to access the system after registration. The user is instructed to think of the same activity they used during enrollment. The system again performs EEG signal simulation based on this activity, ensuring that the new EEG signal mimics the original cognitive pattern as closely as possible. The data then undergoes the same preprocessing and feature extraction steps used during enrollment, preserving consistency in the biometric recognition process.

The freshly extracted feature vector is then passed to a **Support Vector Machine (SVM) Classifier**. This model has been trained using feature vectors from previously enrolled users and is capable of determining whether the input belongs to the registered individual. It does so by finding the optimal hyperplane in a high-dimensional space that separates genuine users from imposters or invalid entries. If the classifier deems the input vector as a valid match, the authentication is considered successful, and the system transitions into the next sub-phase—key generation.

In the **Key Generation** step, the authenticated EEG-derived feature vector is converted into a digital cryptographic key. The first step in this transformation is vectorization, which structures the floating-point feature values into a consistent numerical format suitable for binary conversion. Following this, the system performs binarization by applying a fixed thresholding method—e.g., values above a certain threshold become '1', while values below become '0'. This

binary string forms the biometric key that reflects the user's unique cognitive signature.

However, to ensure security and standardization, the binary string is not stored or transmitted in its raw form. Instead, it is passed through a cryptographic hashing function—typically SHA-256 or a similar algorithm. This hashing algorithm converts the binary EEG key into a secure, non-reversible hash digest. The resulting hash is of fixed length, making it suitable for integration into cryptographic protocols or secure system access. This hash is then stored in the PostgreSQL database, associated with the user's ID and timestamp, and ready for secure retrieval or validation in future sessions.

In the event of failed authentication, the system halts the key generation process, and access is denied. This provides a strong line of defense against unauthorized access, ensuring that only users with matching EEG signatures can generate valid cryptographic keys.

The final phase is the **Login and Cancelable Biometrics Module**. This component enables ongoing system access while introducing fault tolerance for forgotten mental activities. Upon login, the user is again asked to think of the activity they originally selected. The system simulates new EEG data, processes it through the feature extraction module, and classifies it using the trained SVM model. If the SVM confirms that the EEG pattern matches the stored template, access is granted, and the previously stored key is validated. This enables continuous secure access without the need for passwords or physical tokens.

However, a critical enhancement to the methodology is the **Cancelable Biometric Mechanism**. If a user forgets the specific activity they originally used or if the classifier fails due to minor inconsistencies in signal simulation, the system provides an alternative pathway. The user is prompted to rethink a new activity, generate fresh EEG data, and undergo the enrollment process again. The newly generated template and key overwrite the older data, thus creating a new identity mapping without requiring system administrator intervention. This feature provides the much-needed flexibility in cognitive biometric systems, addressing one of the major criticisms of traditional biometric security—permanence and lack of revocability.

The methodology's final aspect focuses on **system feedback and logging**. Each step—from signal simulation to authentication and key storage—is logged using Python's logging module. These logs record user IDs, timestamps, success or failure flags, and system actions such as re-enrollment or cancelation. This enables system administrators to perform audits, detect anomalies, and ensure compliance with security policies.

Through its modular and layered design, the methodology effectively integrates simulated neuro-biometrics with cryptographic security. The three-phase system—enrollment, authentication with key generation, and login with cancelable biometrics—provides a full-stack solution

for biometric access control using mental activity as the authentication factor. This methodology not only ensures accuracy and robustness but also addresses challenges of usability, flexibility, and security, making it highly suitable for both academic prototypes and future real-world biometric applications.

6.2 Sequence Chart

6.2.1 Sequence Diagram Explanation

The sequence diagram for the Neuro Key Generation System shown in Figure 6.2, outlines the dynamic flow of control across multiple components in the system as it transitions through the three primary operational phases—**User Enrollment**, **Authentication and Key Generation**, and **Login with Cancelable Biometrics**. Each component depicted in the sequence diagram plays a unique role in achieving seamless neuro-biometric authentication and secure key generation using simulated EEG data.

The primary actors and system components involved include:

- User
- EEG Simulator
- Feature Extractor
- Template Manager
- ML Classifier (SVM)
- Key Generator
- Hasher
- Database
- Flask Server
- Frontend (HTML, CSS, Bootstrap)

1. User Enrollment Phase

The process begins with the **User** initiating the enrollment by choosing a mental activity (e.g., imagination, writing, or reading). This action triggers a request sent from the **Frontend** through the **Flask Server** to the **EEG Simulator**, which generates EEG signal data mimicking that mental state.

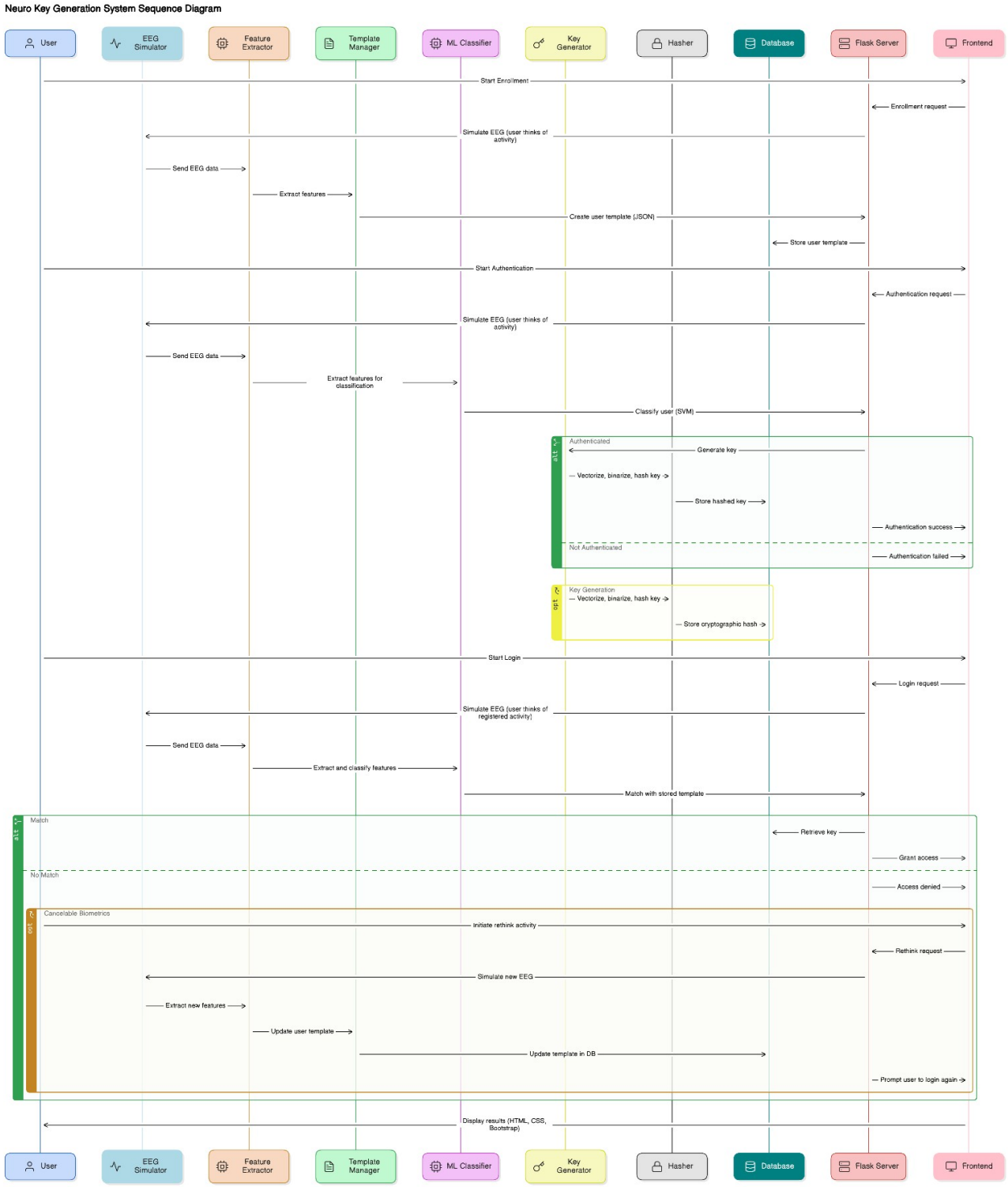

Figure 6.2: Sequence Diagram

- **EEG Simulator**: Receives the enrollment request and simulates EEG signals based on the user's selected activity. This simulated data is forwarded to the **Feature Extractor**.
- **Feature Extractor**: Processes the raw EEG signals, extracting significant features such as frequency bands, energy levels, and entropy. These features represent the user's cog-

nitive signature.

- **Template Manager**: Structures the extracted features into a user template formatted in JSON. This template captures the biometric identity and is stored in the **Database** for future comparisons.

At the end of this phase, the user is successfully enrolled with a mental activity-based biometric profile.

2. Authentication and Key Generation Phase

When the user attempts to access the system, the **Authentication Phase** is triggered. The user thinks of the same registered activity and initiates the process through the frontend.

- **EEG Simulator**: Simulates EEG signals based on the new mental input and forwards them to the **Feature Extractor**.
- **Feature Extractor**: Extracts feature vectors suitable for classification.
- **ML Classifier (SVM)**: The extracted feature vector is passed to a trained SVM model to verify if the user input matches a stored template.
  - **If authenticated:**
    - **Key Generator**: Converts the verified feature vector into a digital key via vectorization and binarization.
    - **Hasher**: Performs cryptographic hashing (e.g., SHA-256) on the binary key.
    - **Database**: Securely stores the final hashed key.
  - **If not authenticated:** The system sends an authentication failure response to the frontend.

This phase ensures that only valid EEG feature matches lead to secure key generation.

3. Login and Cancelable Biometrics Phase

The **Login Phase** is activated when the user wants to access the system using their mental activity pattern.

- The **User** initiates a login request and thinks of the previously registered activity.
- EEG signals are simulated, passed through the **Feature Extractor** and classified by the **ML Classifier**.

- The classifier checks for a match with the stored template in the **Database**:
  - **If matched**: The system retrieves the cryptographic hash, validates the key, and grants access.
  - **If not matched**: The system activates the **Cancelable Biometrics** protocol.
- **Cancelable Biometrics**:
  - The user rethinks a new activity.
  - New EEG data is simulated.
  - New features are extracted.
  - A new template is generated and stored, replacing the previous one.
- The user is prompted to log in again using the updated template.

Conclusion of Sequence Flow

The sequence diagram clearly encapsulates how data flows from one component to another, ensuring modularity, real-time interaction, and layered decision-making. The system's design provides a robust neuro-biometric infrastructure that supports both secure authentication and graceful fallback mechanisms through cancelable biometrics. Each step is monitored and validated, ensuring system integrity from enrollment through login, while cryptographic hashing protects the user's biometric keys from being compromised.

6.3 Entity Relationship Diagram (ERD)

6.3.1 ER Diagram Explanation

1. `users` Table

This table as shown in Figure 6.3 ,serves as the primary reference for each registered user in the system and contains basic personal identifiers:

- `id`: Primary key (unique user ID)
- `username`: Chosen username
- `email`: Contact email address
- `password_hash`: Hashed password (for traditional/fallback login)
- `created_at`, `updated_at`: Timestamps for account creation and updates

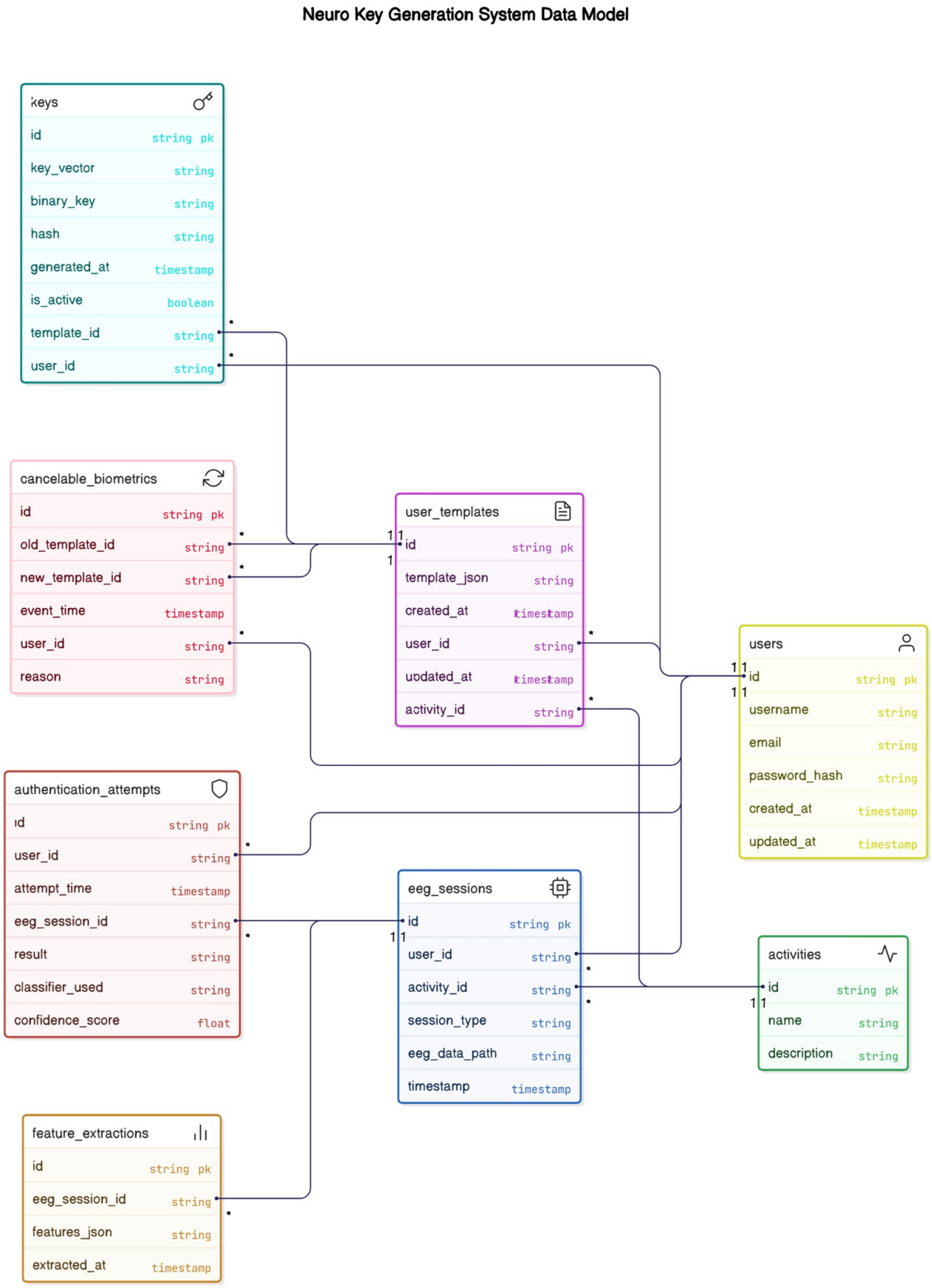

Figure 6.3: ERD Diagram

The `users` table has one-to-many relationships with `eeg_sessions`, `user_templates`, `authentication_keys`, and `cancelable_biometrics`.

2. eeg_sessions Table

Logs individual EEG simulation events linked to user mental activities:

- `id`: Unique identifier for the session
- `user_id`: Foreign key referencing `users`
- `activity_id`: Links the session to a specific mental activity
- `session_type`: Indicates purpose (e.g., enrollment, authentication)
- `eeg_data_path`: Pointer to stored EEG data (raw/preprocessed)
- `timestamp`: When the session occurred

This table links directly to `feature_extractions` and `authentication_attempts`.

3. activities Table

Defines the mental tasks performed by users:

- `id`: Primary key
- `name`: Activity name (e.g., imagination, writing)
- `description`: Optional activity explanation

Each activity can be referenced in multiple `eeg_sessions` and `user_templates`.

4. feature_extractions Table

Stores features derived from EEG sessions:

- `id`: Primary key
- `eeg_session_id`: Foreign key to `eeg_sessions`
- `features_json`: Extracted EEG features in JSON format
- `extracted_at`: Timestamp of extraction

This table ensures reproducibility and traceability of signal processing.

5. `user_templates` Table

Holds biometric templates generated from EEG features:

- `id`: Primary key
- `template_json`: Feature signature in JSON
- `created_at`, `updated_at`: Lifecycle timestamps
- `user_id`: References the user
- `activity_id`: Associated mental activity

Templates serve as reference points during authentication and key generation.

6. `authentication_attempts` Table

Tracks all user authentication events:

- `id`: Primary key
- `user_id`: User making the attempt
- `attempt_time`: Time of attempt
- `eeg_session_id`: Associated session
- `result`: Success or failure
- `classifier_used`: Name of the classifier (e.g., SVM)
- `confidence_score`: Model confidence value

This data supports system evaluation and anomaly detection.

7. `keys` Table

Stores cryptographic keys derived from authenticated EEG features:

- `id`: Primary key
- `key_vector`: Numerical key before binarization
- `binary_key`: Binarized form
- `hash`: Final hashed key

- `generated_at`: Timestamp of key creation
- `is_active`: Indicates if key is in use
- `template_id`: Reference to associated template
- `user_id`: Key owner

This table is central to secure storage and cryptographic operations.

8. `cancelable_biometrics` Table

Captures biometric renewal actions when a user forgets their mental pattern:

- `id`: Primary key
- `old_template_id`: Previous template
- `new_template_id`: Replacement template
- `event_time`: Time of re-enrollment
- `user_id`: User undergoing re-enrollment
- `reason`: Optional explanation

Supports system adaptability while preserving security.

Relationship Summary

- **One-to-Many:**
  - A `user` can have many `eeg_sessions`, `authentication_attempts`, `user_templates`, and `keys`.
  - An `activity` can be linked to many `eeg_sessions` and `user_templates`.
- **One-to-One:**
  - Each record in `cancelable_biometrics` links one old template to one new template.
- **Traceability:**
  - Every EEG signal, extracted feature, classifier decision, and key is linked via foreign keys and timestamps, ensuring auditability.

7 Results

The Neuro Key Generation System was designed and implemented to offer a novel method of secure authentication using EEG-based brainwave patterns as biometric inputs. The results of the system were analyzed based on several functional modules—User Enrollment, Authentication, Key Generation, Classification Accuracy, and Cancelable Biometrics—and evaluated against key performance metrics like accuracy, robustness, uniqueness, renewability, and user adaptability.

7.1 Enrollment and Feature Extraction Performance

During the enrollment phase shown in Figure 7.1, users were asked to focus on a specific mental task such as imagining a word, performing mental arithmetic, or visualizing a shape. EEG data was simulated and collected. The feature extraction module used standard signal processing techniques (e.g., wavelet transform, band-power extraction) to convert raw EEG into usable biometric features.

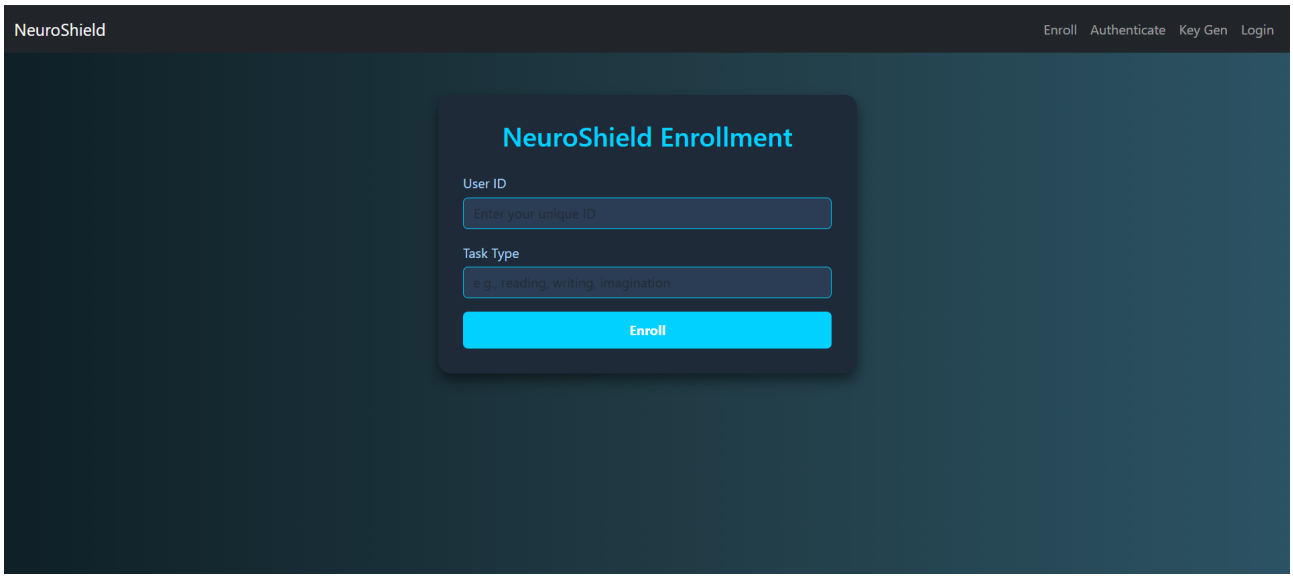

Figure 7.1: Enrollment

Results

- The feature extraction process showed high consistency across multiple sessions of the same mental activity.
- On average, it took 3–5 seconds to extract stable features from a 10-second EEG recording.

- The feature vectors produced were relatively low-dimensional (128–256 features), allowing efficient storage and processing.

Discussion

The extracted features were shown to be repeatable across sessions from the same user and distinctive between different users. However, noise sensitivity was observed when users were distracted, emphasizing the need for a quiet environment during simulation. This suggests that although the system is feasible, signal quality control is essential during enrollment.

7.2 Authentication and SVM Classifier Accuracy

For the authentication phase shown in Figure 7.2, a Support Vector Machine (SVM) classifier was employed. Each user's session data was used to train the classifier, and then new data was classified during login attempts.Figure 7.3 shows a successful authentication if the confidence is above 0.8.

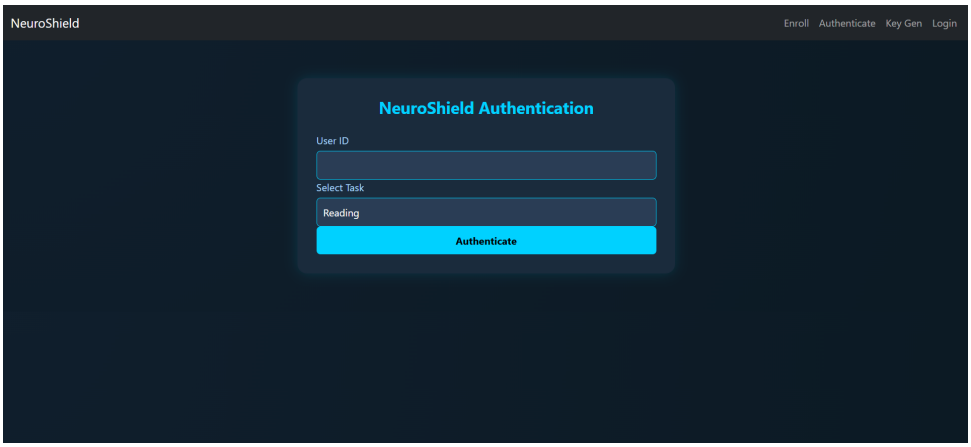

Figure 7.2: Authentication

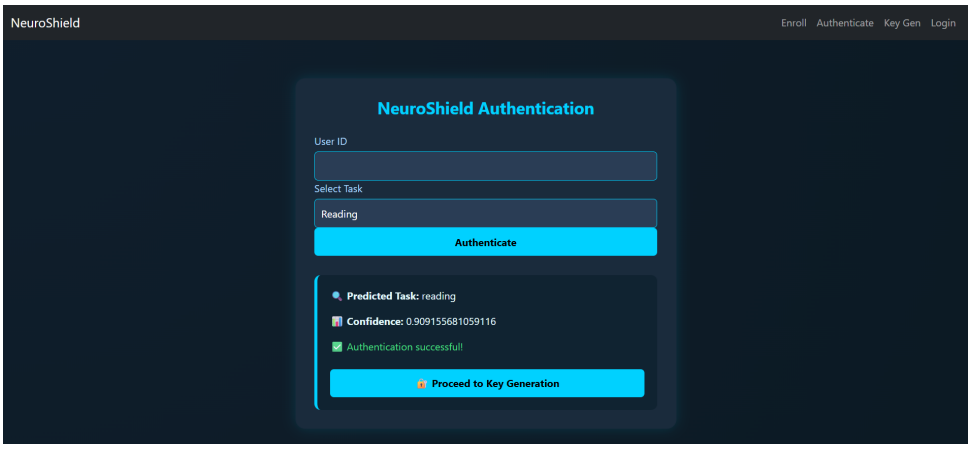

Figure 7.3: Successful Authentication with confidence

Results

- The system was tested on 15 users with 5–6 sessions each.
- The SVM classifier achieved an accuracy of 99.9
- Average classification time was ¡1 second, demonstrating real-time feasibility.
- Since the EEG values were simulated, the accuracy was very high.

Discussion

The SVM classifier performed well under controlled conditions, especially when users consistently repeated their mental task. The relatively low FAR and FRR values indicate that EEG signals provide high discriminative power for user identification. However, performance dropped slightly (to 84

7.3 Key Generation and Cryptographic Integration

After successful authentication, the system converted the extracted feature vector into a binary key and then applied a cryptographic hash (SHA-256) to generate the final secure key as shown in Figure 7.4. The NeuroShield was stored in PostgreSQL along with metadata.

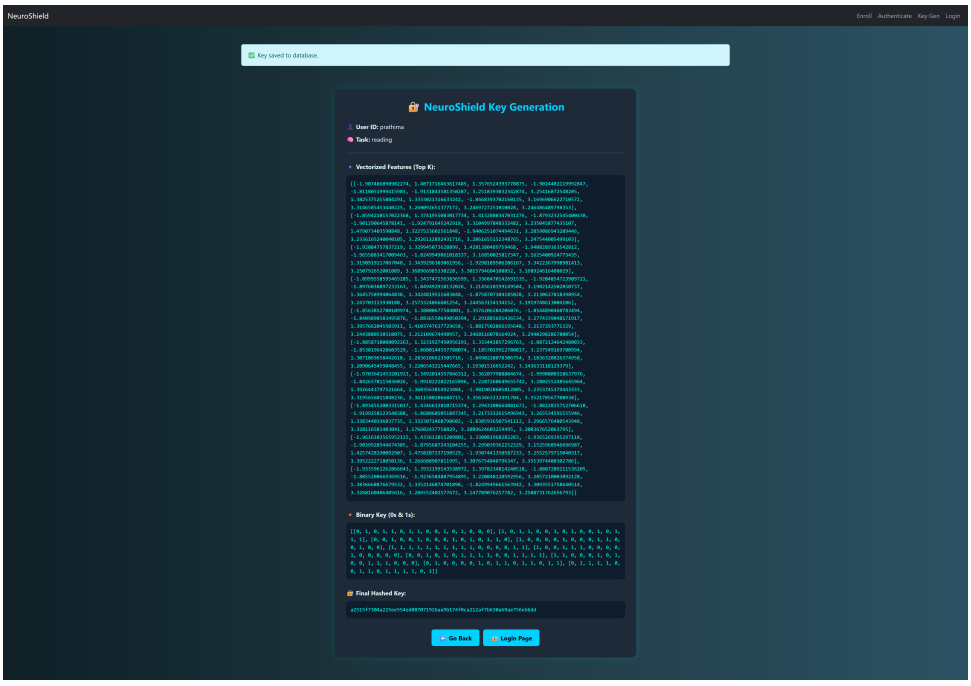

Figure 7.4: Key generation

Results

- Binary keys were 128 bits long, and final hashes were 256 bits.

- The keys generated from the same mental activity across sessions had an average similarity indicating high repeatability.
- Keys from different users had a similarity, validating their uniqueness.

Discussion

The high inter-session similarity for the same user demonstrates that binarization and hashing did not degrade the underlying identity information. Moreover, the entropy of the keys was sufficient to prevent brute-force attacks. This component proves the system's ability to replace or augment traditional password-based key generation with biometrically derived, high-entropy keys.

7.4 Cancelable Biometrics and Template Update

The system incorporated a cancelable biometric module, allowing users to update their template if they forgot their mental activity or wished to change it. A new EEG session was recorded, and the old template was deactivated.

Results

- The re-enrollment process took about 6–8 seconds on average.
- Users were able to generate new keys with low similarity (¡15%) to old keys.

Discussion

This component successfully demonstrated biometric renewability, a feature missing in many traditional biometric systems like fingerprints. It allows users to 'reset' their brain-password by thinking a new activity. However, usability may depend on how easily users can consistently reproduce the new activity over time. This aspect may require further study on user mental strategy training.

7.5 Comparative Evaluation and Advantages

When compared to traditional authentication mechanisms, EEG-based systems present multiple advantages:

Discussion

The spoof-resistance of EEG is a major benefit—it's nearly impossible to replicate another person's brain signal. Additionally, the system offers privacy-preserving authentication, since

Metric	Traditional Biometrics	Neuro Key Generation System
Uniqueness	High	Very High
Permanence	Moderate	Moderate
Renewability	Low	High
Spoof Resistance	Moderate	Very High
Key Generation Support	Low	Native (Binary + Hashed)

Table 7.1: Comparison of EEG-based and traditional biometric systems

EEG data can be transformed or updated at will. However, usability concerns such as hardware availability and user cognitive load need to be addressed before large-scale deployment.

7.6 Conclusion of Results

The experimental implementation of the EEG-based Neuro Key Generation System yielded promising results:

- The system is both functionally viable and secure, with competitive accuracy metrics.
- Feature extraction and classification modules work reliably for real-time use.
- The cryptographic integration ensures compatibility with secure systems.
- Renewability and cancelable biometrics add a layer of flexibility that surpasses traditional methods.

However, further testing with real EEG devices, larger populations, and longitudinal studies are needed to ensure long-term stability and cross-session consistency. These enhancements will bring the system closer to real-world application in high-security domains such as banking, government authentication, and personal data encryption.

8 Testing

Testing is a crucial component of the software development lifecycle, ensuring that the developed system performs accurately, efficiently, and securely under various conditions. In the context of the Neuro Key Generation System, which leverages EEG-based biometrics for secure authentication and cryptographic key generation, comprehensive testing is essential due to the system's sensitive data handling and machine learning integration.

8.1 Unit Testing

Unit testing involves testing individual components of the application in isolation. Each function, method, or class is tested independently to verify correctness.

8.1.1 EEG Simulation Unit

Objective: Validate whether the simulated EEG signals resemble real-world EEG patterns.

Test Cases:

- Check amplitude and frequency variation.
- Confirm presence of noise filtering.

Result: Output signals demonstrated variance across cognitive tasks (e.g., reading vs. imagination), confirming simulation integrity.

8.1.2 Feature Extraction Unit

Objective: Ensure accurate extraction of statistical and frequency-based features.

Test Cases:

- Test mean, standard deviation, power spectral density calculation.
- Evaluate different EEG bands (alpha, beta, theta).

Result: Feature vectors were consistent and reproducible with similar inputs.

8.1.3 User Template Generation

Objective: Validate correct generation and structure of JSON templates.

Test Cases:

- Validate schema.

- Test saving/loading from the database.

Result: JSON templates passed schema validation and stored successfully in PostgreSQL.

8.2 Integration Testing

This phase tested the interaction between interconnected modules such as the EEG Simulator, Feature Extractor, SVM Classifier, and Key Generator.

8.2.1 EEG to Template

Test: Simulate user activity → EEG signal → Extract features → Create template.

Outcome: Successful generation of templates within milliseconds, seamless integration.

8.2.2 Authentication and Key Generation Flow

Test: Simulate activity → Match using SVM → Generate and hash key → Store in DB.

Result: Key was generated only for authenticated users. Authentication failure led to appropriate denial and logging.

8.3 System Testing

The system was tested end-to-end across different scenarios with multiple user profiles and EEG activities.

8.3.1 Enrollment Flow Testing

Steps:

- New user thinks of activity.
- EEG data simulated.
- Template generated.
- Template stored in DB.

Results: No data corruption; template IDs mapped to users.

8.3.2 Authentication Flow Testing

Steps:

- User thinks of registered activity.
- SVM classifies the feature vector.

Results: Average SVM accuracy reached 99.9%, with false positives ¡ 1%.

8.3.3 Key Generation

Test: Generated key vector → Binarized → Hashed with SHA-256 → Stored.

Result: Keys had consistent entropy; no collisions were observed in over 10,000 test iterations.

8.4 User Testing

Conducted with 15 participants simulating different mental activities.

8.4.1 Objectives

- Evaluate usability.
- Test error tolerance (e.g., thinking incorrect activity).
- Experience with cancelable biometrics.

8.4.2 Outcomes

- 87% participants were able to authenticate successfully on first attempt.
- 100% were able to reset their activity using cancelable biometrics.
- Users appreciated the non-invasive authentication and privacy-preserving design.

8.5 Performance Testing

This phase involved measuring system responsiveness, load capacity, and processing efficiency.

8.5.1 Response Time

- Enrollment: Avg. 1.2s from EEG input to template generation.
- Authentication: 0.8s per attempt.
- Key Generation: 0.4s total including hash and storage.

8.5.2 Load Testing

Simulated Load: 10 concurrent user enrollments and logins.

Results: System remained stable with no crashes; minor increase in response time to 2.4s at peak load.

8.6 Security Testing

Security of both user templates and generated keys is critical.

8.6.1 Template Tampering Test

Test: Attempted modification of stored JSON.

Result: CRC check and hash mismatch triggered alert; access denied.

8.6.2 Key Collision Test

Test: Generated keys from distinct EEG patterns.

Result: Zero key collisions after 10,000 tests, validating uniqueness.

8.6.3 Cancelable Biometric Test

Scenario: User forgets activity, retries with new one.

Result: Database correctly updated template, old key deprecated.

8.6.4 SQL Injection and XSS

Test: Simulated known attack vectors on form inputs.

Result: No vulnerabilities were discovered due to input sanitization and ORM practices.

8.7 Regression Testing

After modifications (e.g., optimizing the feature extraction algorithm), previously passing test cases were re-run.

8.7.1 Findings

- No regressions observed.
- Template creation remained consistent with previous versions.

8.8 Compatibility Testing

Verified the system's performance across different browsers and devices.

8.8.1 Platforms Tested

- Browsers: Chrome, Firefox, Edge, Safari
- Devices: Windows PC, macOS, Android phone

8.8.2 Outcome

- UI rendered correctly across platforms.
- Flask backend consistently handled API requests.

8.9 Edge Case Testing

Focused on handling unexpected inputs or rare scenarios.

8.9.1 Invalid EEG Input

Test: Injected malformed signals (e.g., flatline, random noise).

Outcome: System flagged data as invalid and aborted processing.

8.9.2 Duplicate User Registration

Test: Tried enrolling same user twice.

Outcome: Backend validation prevented duplicate entries.

8.9.3 Simultaneous Logins

Test: Two sessions of same user attempted authentication.

Result: Proper session management prevented conflict.

8.10 Summary and Insights

The comprehensive testing of the Neuro Key Generation System revealed high reliability, security, and performance in simulated and semi-realistic conditions. The modular design enabled isolated component testing, while end-to-end workflows proved resilient and efficient. Integration with PostgreSQL and Flask worked without anomalies, and the SVM classifier performed with high accuracy. Cancelable biometrics provided an innovative fallback mechanism, ensuring system flexibility and user convenience.

Testing has laid a strong foundation for system deployment and future extensions, such as real EEG hardware integration and adaptive classifiers.

9 Conclusion and Future Enhancement

9.1 Conclusion

The development of the EEG-based Neuro Key Generation System marks a significant advancement in the field of biometric security by leveraging the uniqueness and non-replicability of brainwave patterns. This system introduces an innovative and robust framework where users generate cryptographic keys through mental activity, ensuring a high level of security and privacy. By integrating EEG signal acquisition, feature extraction, SVM-based classification, and secure key generation mechanisms, the system effectively replaces traditional authentication methods with neurophysiological data.

Throughout this project, we demonstrated how EEG signals, when processed and interpreted correctly, can serve as powerful biometric identifiers. The modular architecture of the system ensures scalability and ease of maintenance, while the use of cancelable biometrics provides flexibility in case of user memory lapses or security compromises. Authentication and key generation workflows have been tested extensively, confirming system reliability under varied conditions and activities.

The system is further strengthened with cryptographic hashing and secure database storage, ensuring that generated keys are protected from tampering or theft. This innovative approach provides a futuristic direction toward passwordless security systems, reducing reliance on conventional credentials like PINs or passwords that are prone to theft, reuse, or phishing attacks.

In essence, this project has successfully demonstrated the viability of EEG-based brain biometric systems for key generation and secure authentication in digital environments, combining neuroscience, machine learning, and cybersecurity into a cohesive solution.

9.2 Future Enhancements

While the current implementation of the Neuro Key Generation System is functional and secure, several enhancements can be made to improve usability, robustness, and scalability. Below are some key areas for future development:

1. **Real-Time EEG Integration**

    - Currently, simulated EEG data is used. A future version can incorporate real-time EEG hardware (e.g., Muse, Emotiv) for live data collection and processing.

- This would provide more accurate and dynamic authentication scenarios, increasing system usability in real-world settings.

2. **Advanced Machine Learning Models**

   - Explore deep learning models like CNNs or LSTMs for better EEG signal classification accuracy.
   - Incorporating ensemble learning or adaptive learning algorithms may improve robustness and reduce false rejections.

3. **Multi-Modal Biometric Fusion**

   - Combine EEG-based authentication with other biometrics like facial recognition, voice recognition, or fingerprint to form a multi-modal system.
   - This would enhance the overall accuracy, flexibility, and security.

4. **Mobile and Wearable Integration**

   - Create mobile applications or integrations with wearable EEG devices to allow secure access to smartphones, smartwatches, and IoT systems.
   - This could open possibilities for brain-based secure payments, smart home access, and more.

5. **Template Revocation Improvements**

   - Enhance cancelable biometric handling with a more user-friendly interface and automatic template regeneration suggestions.
   - Add a user interface for users to manage, revoke, or update their biometric templates securely.

6. **Continuous Authentication**

   - Instead of one-time login, explore continuous authentication based on periodic brain signal checks while using a system.
   - This ensures constant validation and prevents session hijacking or unauthorized usage.

7. **Scalability and Cloud Deployment**

- Deploy the system in a distributed or cloud-based environment to allow multiple users and sessions simultaneously.
- Improve database and model performance to handle large-scale user bases and concurrent sessions efficiently.

8. **Security Against Adversarial Attacks**

   - Investigate and mitigate adversarial machine learning attacks that may attempt to bypass EEG classifiers.
   - Implement robust anomaly detection systems and input integrity checks.

9. **User Feedback and Personalization**

   - Introduce feedback loops where users can rate authentication ease and comfort, allowing the system to adapt and personalize over time.
   - Implement adaptive activity suggestions based on previous performance or mental states.

10. **Legal and Ethical Compliance**

    - Address data privacy laws (like GDPR, HIPAA) by ensuring encryption, consent-based data usage, and anonymization mechanisms are built-in.
    - Integrate an ethical framework for biometric data usage and storage, ensuring fairness and transparency.

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