University of Novi Sad
Technical faculty "Mihajlo Pupin" Zrenjanin

Proceedings of the 14th International Conference on Applied Internet and Information Technologies AIIT 2024

8 November, 2024, Zrenjanin, Serbia

AIIT

International Conference

University of Novi Sad
Technical faculty
"Mihajlo Pupin"
Zrenjanin
Republic of Serbia

XIV INTERNATIONAL CONFERENCE ON APPLIED INTERNET AND INFORMATION TECHNOLOGIES

AIIT 2024
PROCEEDINGS

November 8, 2024
Zrenjanin
Serbia

Proceedings publisher and organizer of the conference:
University of Novi Sad, Technical faculty “Mihajlo Pupin”, Zrenjanin, Republic of Serbia

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e-Proceedings
ISBN 978-86-7672-379-9

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CIP - Каталогизација у публикацији
Библиотеке Матице српске, Нови Сад

004(082)(0.034.4)

INTERNATIONAL Conference on Applied Internet and Information Technologies (14 ; 2024 ; Zrenjanin)
Proceedings [Elektronski izvor] / XIV International Conference on Applied Internet and Information Technologies AIIT 2024, Zrenjanin, November 8th, 2024 ; [organizer] Technical Faculty "Mihajlo Pupin", Zrenjanin ; [editors Ivana Berkovic, Kostandina Veljanovska]. - Zrenjanin : Tehnički fakultet "Mihajlo Pupin", 2024. - 1 elektronski optički disk (CD-ROM) : tekst, ilustr. ; 12 cm

Sistemski zahtevi: Nisu navedeni. - Naslov sa nasl. ekrana. - Elektronska publikacija u formatu pdf opsega 504 str. - Bibliografija uz svaki rad. - Registar.

ISBN 978-86-7672-379-9

a) Информационе технологије -- Зборници

COBISS.SR-ID 158823945

Introduction

International Conference on Applied Internet and Information Technologies is an annual Conference that we started in 2012 after successful results of the International Conference on Information and Communication Technologies for Small and Medium Enterprises in 2011. This year, the fourteenth Conference is hosted in Zrenjanin and presents collaboration between the University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, Serbia and the University "St. Kliment Ohridski", Faculty of Information and Communication Technologies - Bitola, Republic of North Macedonia.

The Conference was financially supported by the Provincial Secretariat for Higher Education and Scientific Research, Novi Sad. The Technical Faculty "Mihajlo Pupin" has provided the necessary technical support.

This year we had gathered our colleagues, scientists, researchers and students from 13 countries: Canada, USA, India, Russia, Germany, Denmark, Georgia, Slovakia, Hungary, Croatia, Bosnia and Herzegovina, North Macedonia and Serbia. They presented papers and promote the results of research and scientific work in the field of information technology. Out of more submitted papers, 66 were selected for presentation on Conference and publishing in Proceedings.

Some of Conference topics are: Artificial Intelligence, Intelligent Systems, Data Science, Big Data Technologies, Business Intelligence, IT Support to Decision-making, Information Systems, Software Engineering and Applications, Communications and Computer Networks, Data and System Security, Computer Graphics and Visualization, IT Management, etc.

During the conference were organized in six sessions: two plenary sessions, two Oral Sessions and two Poster sessions. The introductory lectures were:

- *Text Mining,* held by Slavica O'Connor, Canada,
- *IT equipment and software for training, modeling and data analysis for flood and forest fire prevention, protection and management in project SOLVE,* held by Andrijana Bocevska, North Macedonia,
- *Reducing Manual Labeling Effort by Identifying the Most Informative Unlabeled Data via Active Learning,* held by Velibor Ilić, Serbia,
- *Digital platform for monitoring and forecasting the environmental situation of the Baikal natural territory,* held by Igor V. Bychkov, Russia.

The AIIT program committee would like to thank the authors of the papers for their contribution. All submitted papers were peer-reviewed by members of the committee and the other eminent reviewers. All submitted papers were peer-reviewed through the double-blind review process. Also, the AIIT program committee would like to express special gratitude to the reviewers for their tremendous work done for selecting the papers with their valuable comments and suggestions that contributed to improve the quality of the papers.

AIIT 2024 was very successful conference with fruitful exchange of experiences among the participants and contribution to the further development of Internet and Information technologies research.

Next year the conference will be held in Bitola.

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PLENARY PAPERS

Adaptive Biometric Systems: Challenges and Opportunities

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Abstract:
Adaptive biometric systems represent a significant advancement in authentication technologies, designed to dynamically update biometric templates to maintain high accuracy and security over time. This paper examines the key strategies for adapting these systems, focusing on their ability to evolve as users' biometric data changes due to factors like aging, environmental shifts, or behavioural variations. Central to this process are adaptation mechanisms, such as additive and replacement techniques, which continuously update biometric templates to reflect new data while maintaining the integrity of the system. Key criteria for adaptation include oracle-based methods, request acceptance, and dual thresholds, which help determine when and how the system should adapt. Adaptation modes, whether supervised or semi-supervised, guide how templates are updated based on labelled or unlabelled data. Both offline (delayed) and online (real-time) adaptation methods offer distinct advantages, depending on system requirements. Despite their benefits, adaptive biometric systems face significant challenges, particularly in large-scale applications, data acquisition, and security risks such as poisoning attacks. Addressing these challenges, including the development of secure, scalable, and resource-efficient solutions, is crucial for the widespread adoption of adaptive biometric systems, especially in mobile and commercial contexts.

Keywords:
biometric pattern, biometric template, adaptive biometric systems, biometric databases.

1. Introduction

This paper aims to investigate adaptive biometric systems, which dynamically update biometric templates to improve identification accuracy and security, to improve their functionality. The introductory section explains the importance of adaptive biometric systems, focusing on their role in improving the accuracy and security of authentication [1], Section 2 covers adaptation strategies, including models for updating biometric templates and the mechanisms involved in their adaptation [2], [3], Section 3 discusses adaptation criteria, which define when and how biometric data in systems are updated [4], [5], Section 4 deals with the adaptation mode, explaining the methods of supervised and semi-supervised system adaptation. Section 5 explores adaptation mechanisms, analysing different approaches for dynamically updating biometric templates. Section 6 highlights open challenges, such as system scalability, security issues, and the need for improved test databases. The conclusion highlights that while adaptive biometric systems offer significant benefits, the challenges remain, particularly in security and adaptability.

2. Strategies for adaptation of the biometric template

Adaptation strategies in biometric systems are essential for improving system performance and accuracy over time. These strategies, shown in Fig. 1, are typically structured around several key components:

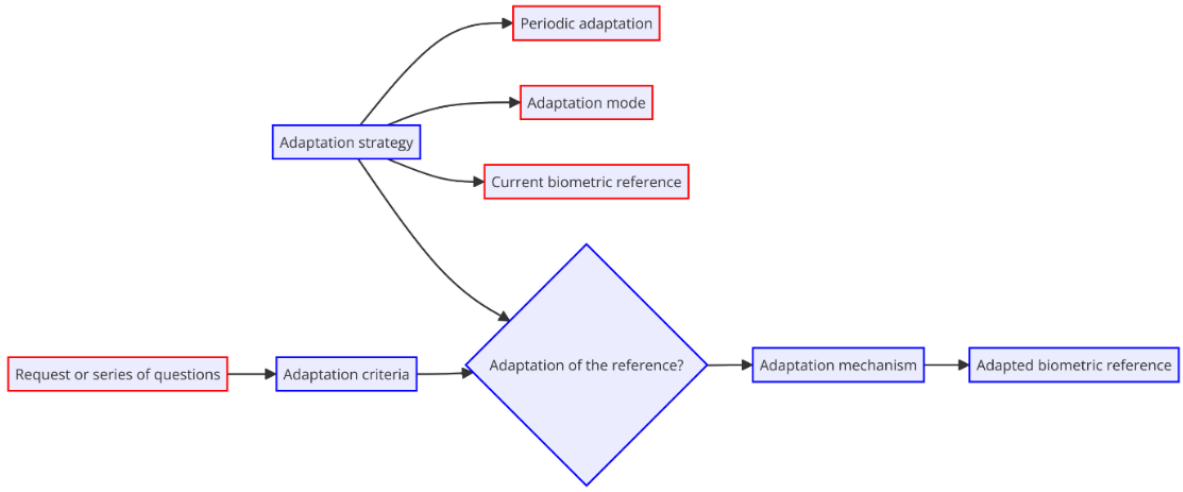

Figure 1: Generic flowchart of the biometric adaptation process.

- Reference modelling defines the structure and method for modelling the biometric template.
- Adaptation criteria determine the conditions under which the adaptation mechanism is triggered.
- Adaptation mode specifies the method used for assigning labels to biometric templates, which can be supervised or semi-supervised.
- Adaptation periodicity establishes the frequency at which the adaptation process is applied, whether in real-time (online) or periodically (offline).
- Adaptation mechanism outlines the specific steps that are taken once the adaptation criteria are met.

These strategies ensure that biometric systems can evolve and adapt to new data and environmental changes, improving their reliability and accuracy over time.

2.1. Reference Modelling in Adaptive Biometric Systems

Reference modelling plays a key role in adaptive biometric systems, addressing the need to adapt biometric templates over time to improve identification accuracy and reliability. During the authentication process, the user's biometric characteristics may vary due to factors such as emotional state, health conditions, or changes in the environment. These strategies are usually based on classification algorithms and biometric template update mechanisms.

In adaptive biometric systems, biometric templates are generally categorized into three main types [5]:

• A single-sample biometric template usually consists of a single sample obtained during the registration phase. Although simple, it has limitations, especially for behavioural modalities that exhibit significant variability, such as keystroke dynamics. Research shows that while this method may be sufficient for physical modalities with less variability, behavioural modalities often require multiple samples to achieve stability and accuracy [6].

• Multi-sample biometric template (galleries) involves collecting multiple samples during the registration phase and storing them in a biometric template gallery. The use of multiple samples minimizes errors, as it accounts for variations in the user's biometric data [7].

• Multiple templates per user is a method that maintains several biometric templates for each user, customizing them over time by incorporating new samples. This provides a more accurate representation of the user's current state, accommodating variations in biometric characteristics. Techniques such as clustering can automatically organize patterns into groups, with the most representative samples used as prototypes, improving system accuracy while reducing memory and processing requirements.

2.1.1. Adaptation Strategies

Adapting biometric systems involves various strategies that enable them to adjust to changes in a user's biometric data, as illustrated in Fig. 2. Key factors in developing these strategies include:

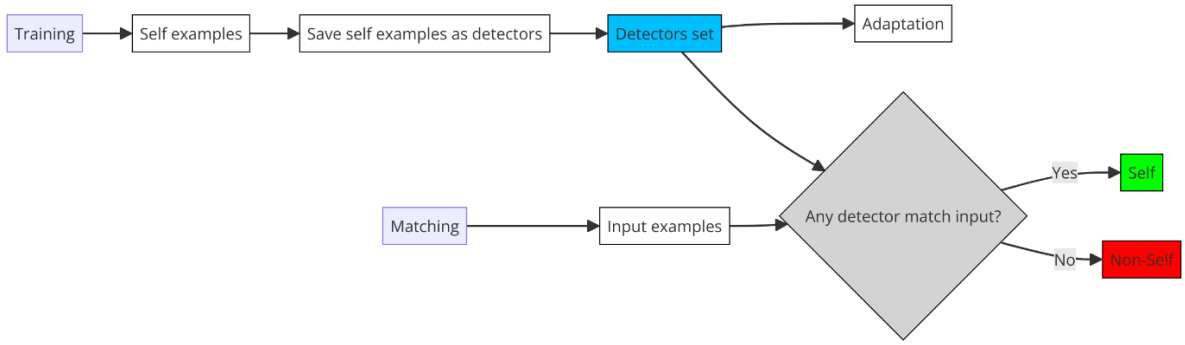

Figure 2: Algorithm for adaptive positive selection

• *Adaptation criterion*, which uses various triggers such as system performance changes or new user data to initiate adaptation.
• *Adaptation mode*, where adaptation can be either supervised or semi-supervised depending on whether the update process is automated or requires human intervention.
• *Adaptation periodicity*, where adaptation can occur either online, with each recognition event, or offline, periodically.

By improving adaptation models and developing new classification algorithms, biometric systems can significantly enhance their accuracy and reliability over time, thereby providing a higher level of protection for users.

3. Adaptation Criteria in Biometric Systems

Adaptation criteria are essential components that determine when and how to adapt a biometric system to maintain or improve its performance. The nature of biometric data, influenced by environmental factors, physiological changes, and operational conditions, demands continuous adjustment to maintain accuracy and security. In the literature, several adaptation criteria have been proposed, and their effectiveness varies depending on the system's needs and the biometric modality used.

Oracle-based Adaptation: The oracle-based approach relies on a human operator (or an equivalent decision-making entity) to decide when the system should undergo adaptation. While this method ensures high accuracy, as it relies on human judgment, it is not always feasible, especially in fully automated systems [8]. In systems requiring minimal human intervention, relying on an operator to monitor each decision is impractical. This approach is particularly useful when the stakes of incorrect classification are high, such as in critical security environments, but the operational cost can be high due to the manual intervention required.

Request Acceptance: The request acceptance criterion is one of the simplest forms of adaptation. In this case, any accepted authentication request is used to update the biometric template. For example, systems that use keystroke dynamics for authentication constantly monitor and update the user’s typing behaviour [9]. Over time, this helps the system adapt to natural changes in a user’s behaviour. However, this approach has limitations, as it risks incorporating incorrectly classified samples into the original biometric template, potentially degrading the system's accuracy.

In keystroke dynamics, for instance, changes in the typing style over time can lead to false rejections. To address this, dynamic updating of training data is recommended to ensure that classifiers remain effective even as typing behaviour evolves. There are two primary update mechanisms: "moving window" and "growing window." The "moving window" method uses a fixed number of recent samples, whereas the "growing window" incorporates all new and original samples.

Dual Threshold Criterion: The dual threshold approach incorporates two distinct thresholds: a decision threshold and an adaptation threshold. Only samples that meet the more stringent adaptation threshold are used to update the system [10]. This minimizes the risk of including false positives in the genuine biometric template. Although this method reduces errors associated with incorporating false samples, its improvement in overall system performance may be limited due to its strict adaptation strategy.

The dual threshold approach is beneficial in environments where it is crucial to limit errors, such as in fingerprint recognition systems, where high security and accuracy are paramount. However, its conservative nature can sometimes prevent the system from adequately adapting to genuine changes in the user's biometric data.

Adaptive Thresholds: The adaptive thresholds method is an enhancement of the dual threshold approach, allowing thresholds to adjust over time [11]. By continuously updating these thresholds, the system can track intra-class variations in user characteristics and adapt more effectively. This method, validated through keystroke dynamics, demonstrated improved authentication performance by reducing error rates compared to fixed thresholds.

In a biometric modality such as keystroke dynamics, where intra-class variation is significant, adaptive thresholds provide flexibility, improving both security and usability. Research has shown that adaptive thresholds reduce equal error rates (EER) by up to 2% compared to static thresholds [11].

Quality Index: The quality index criterion ensures that only high-quality data is incorporated into the biometric template. This index assesses the quality of biometric samples based on various factors, such as sensor performance and environmental conditions. If the data quality is deemed insufficient, the sample is discarded to prevent degrading the template's accuracy [12].

This method is particularly relevant in multimodal biometric systems, where multiple modalities (e.g., face recognition, fingerprint recognition) are used. It ensures that the system adapts only when the new data is reliable, which is crucial when the biometric system operates in uncontrolled environments.

Condition-Sensitive Adaptation: Condition-sensitive adaptation focuses on adjusting the system based on specific conditions during the acquisition of biometric data. For instance, if the lighting or user pose differs significantly from the reference conditions, the system adapts accordingly [13]. This approach ensures that unnecessary samples are excluded, reducing the risk of template contamination. For face recognition systems, which are highly sensitive to environmental changes, condition-sensitive adaptation can significantly improve performance by filtering out low-quality samples and focusing on conditions that resemble the reference environment.

Error Deviation Prediction: The error deviation prediction criterion analyses deviations in system performance to determine when adaptation is necessary. This approach is useful in scenarios where the system needs to monitor for systematic errors, such as false mismatches, which may indicate that the template is becoming outdated. Continuous monitoring of error distributions can guide decisions about when to update biometric templates.

In systems deployed at border control checkpoints, a series of false mismatches may prompt the system to initiate an update. This method helps maintain performance in dynamic, real-world environments where biometric data may evolve over time.

Mixed Criteria: Mixed criteria involve combining multiple sources of information to support adaptation decisions. This method is particularly effective in multimodal biometric systems, where different modalities (such as face and fingerprint recognition) can be leveraged together to improve accuracy [15]. Adaptation is triggered when one modality reaches a mismatch threshold while the other confirms the user's identity. The mixed criteria method allows for more robust adaptation strategies, especially when different biometric modalities exhibit varying degrees of intra-class variability. It has been shown to enhance template update processes and improve overall system performance [14], [15], [16].

4. Adaptation Mode

Adaptation criteria are essential components that determine when and how a biometric system should adapt to maintain or improve its performance. Several adaptation criteria have been proposed in the literature, with their effectiveness varying based on the system's needs and the biometric modality used.

Oracle-based adaptation relies on a human operator or decision-making entity to decide when the system should undergo adaptation. While this method ensures high accuracy, it is not always feasible, especially in fully automated systems. In systems requiring minimal human intervention, relying on an operator is impractical. This approach is useful in critical security environments but comes with high operational costs due to manual intervention [17].

Request acceptance is a simpler form of adaptation where any accepted authentication request updates the biometric template. For example, systems using keystroke dynamics monitor and adapt to changes in typing behaviour over time. However, this can introduce errors if incorrectly classified samples are incorporated. In keystroke dynamics, changes in typing style can lead to false rejections, so dynamic updating of training data through "moving window" or "growing window" mechanisms is recommended.

The dual threshold criterion involves two thresholds—a decision threshold and an adaptation threshold. Only samples that meet the adaptation threshold are used for updates, minimizing the inclusion of false positives but limiting system performance improvement. This method is beneficial in high-security environments like fingerprint recognition but may prevent adaptation to genuine changes [18],

Adaptive thresholds improve upon the dual threshold approach by allowing thresholds to adjust over time, enabling the system to track intra-class variations and adapt more effectively. Research shows that adaptive thresholds, particularly in keystroke dynamics, can reduce error rates compared to static thresholds.

Quality index ensures that only high-quality data is included in the biometric template by assessing biometric samples based on sensor performance and environmental conditions, discarding low-quality data to preserve template accuracy. This method is especially relevant in multimodal systems like face and fingerprint recognition, where adapting only to reliable data is crucial in uncontrolled environments.

Condition-sensitive adaptation adjusts the system based on specific conditions during data acquisition, such as lighting or pose changes, to ensure only relevant samples are used, improving performance in systems like face recognition that are sensitive to environmental changes.

Error deviation prediction analyses deviations in system performance to decide when adaptation is necessary, helping systems monitor systematic errors such as false mismatches. This method is particularly useful in dynamic environments like border control checkpoints, where biometric data can evolve over time.

Mixed criteria combine multiple sources of information to support adaptation decisions. This is effective in multimodal systems, where different modalities like face and fingerprint recognition can be leveraged together. Adaptation is triggered when one modality reaches a mismatch threshold while the other confirms the user's identity, enabling more robust adaptation strategies and improving overall system performance.

4.1. Periodicity of adaptation

The frequency of adaptation refers to how often a biometric system updates its templates. Adaptation can occur either offline (with a delay) or online (in real-time), with each approach having different effects on system performance and complexity [19].

Offline adaptation involves collecting biometric data over time and temporarily storing it. Once enough data is gathered or a certain time has passed, the templates are updated. This approach minimizes the impact on real-time performance since updates occur during inactive periods. The adaptation frequency is typically based on predefined intervals, making it a controlled but slower process [20], While this method is more stable and suitable for systems that don't require immediate updates, it may struggle in environments where frequent changes occur.

Real-time adaptation, on the other hand, updates templates as soon as a decision criterion is met. It allows continuous template adjustments during the user verification process, helping maintain high accuracy as conditions change. However, this adds complexity and processing time because recognition and adaptation happen simultaneously, making it more suitable for environments where biometric data or user behaviours frequently change [21].

The choice between offline and real-time adaptation depends on the system's requirements, resource availability, and desired accuracy. Offline adaptation helps maintain stable system performance and avoids overburdening resources during operation, though it may not be responsive enough for environments that require frequent updates. Real-time adaptation offers immediate responsiveness to changing conditions, but this comes at the cost of added complexity and processing delays. It is particularly useful in critical applications like security and access control, where biometric data and environmental conditions change frequently. However, for systems where stability and minimal processing overhead are prioritized, offline adaptation remains a strong option, allowing periodic updates without disrupting system performance.

5. Adaptation and Additive Mechanism in Biometric Systems

The adaptation mechanism in biometric systems is crucial to maintaining high performance in dynamic environments. As biometric data, such as fingerprints, facial recognition or typing dynamics, evolve over time due to factors such as ageing, changes in lighting or variations in user behaviour, the system needs to update its biometric templates to prevent accuracy degradation. The adaptation process ensures that the biometric system remains resilient and accurate despite these variations. The four basic categories of adaptation mechanisms are presented: additive mechanisms, substitution mechanisms, multi-gallery mechanisms, and selection mechanisms [22].

Additive mechanisms incrementally add new samples to the biometric gallery without removing existing ones. These mechanisms help capture a wider range of within-class variation in a user's biometrics, reducing false rejections that occur when genuine biometric variations are confused with imposter attempts. The augment-update mechanism is one of the earliest studied methods, as explored in studies such as [23], which continuously adds new, original samples to the user's gallery. This method assumes that the new samples are reliable and represent the true variations in the user's biometric data.

The advantage of additive mechanisms lies in their simplicity and ability to handle a wide range of biometric variations. However, a significant drawback is the uncontrolled growth of the biometric gallery over time, which can lead to storage and computational inefficiencies. Mechanisms like Graph Min-Cut use advanced algorithms to add new samples while retaining basic information about the user's biometric patterns without overloading the system's memory [24].

Replacement mechanisms not only add new samples to the gallery, but also remove older or less representative samples. This strategy addresses the limitation of additive mechanisms by preventing the gallery from growing indefinitely. A sliding window mechanism, also known as "First In First Out" (FIFO), replaces the oldest samples in the gallery with newer ones. This keeps the size of the gallery constant, making it manageable and preventing memory overload [25].

More advanced replacement mechanisms, such as MDIST and DEND, prioritize the replacement of samples based on their similarity to other samples in the gallery. MDIST selects samples that are most representative of the user's biometric data by calculating their average distance to other samples in the gallery, while DEND focuses on preserving samples that capture a wide range of variation within the class. Both methods have been shown to improve performance in biometric systems, especially when used in combination with semi-supervised learning techniques [26]. Another innovative replacement mechanism is Least Recently Used (LRU), which replaces the least recently used samples in the gallery. Although efficient in some scenarios, LRU can be computationally expensive, as it requires the system to track the usage frequency of each sample in the gallery [27].

Multi-gallery mechanisms involve managing two or more biometric galleries simultaneously, with each gallery using a different adjustment mechanism. This approach allows biometric systems to benefit from the strengths of multiple adaptation strategies. For example, in a dual parallel configuration, one gallery can use the Growing Window mechanism to save initial user templates, while another gallery can use the Sliding Window to update the system with the latest biometric data. The combined results

of the two galleries improve the system's ability to adapt to user behaviour while maintaining pattern integrity.

Another example is Co-Update, a method that applies the principles of co-training to adaptive biometric systems. In this approach, each gallery corresponds to a different biometric modality, such as face and fingerprint recognition. When one modality confidently classifies a sample, the corresponding gallery for the other modality is updated. This approach leverages the complementary nature of different biometric traits to improve system accuracy and robustness in real-world scenarios [28].

Selection mechanisms aim to reduce the size of the biometric gallery by retaining only the most representative samples. These mechanisms are often used in conjunction with additive mechanisms to manage gallery growth effectively. In the context of template selection, the system identifies the most relevant samples that accurately represent the user's biometric patterns. For example, the DEND algorithm uses hierarchical clustering to group samples based on their similarity and selects the most representative sample from each cluster for inclusion in the gallery [29].

An alternative approach is MDIST, which ranks samples based on their average similarity to other samples in the gallery. Samples with the highest similarity scores are retained, while others are discarded. Selection mechanisms are particularly useful in scenarios where storage limitations or computational efficiency is a concern, as they reduce the overall size of the biometric gallery without sacrificing accuracy [30].

6. Open Challenges

The development of adaptive biometric systems brings numerous challenges, especially in scaling, dataset acquisition, and defence against attacks. These systems must constantly adapt to changes in biometric data over time, such as ageing or environmental factors, to maintain high accuracy and security. Below are some of the key open challenges in adaptive biometric systems [31], [32], [33], [34].

Large-Scale Adaptive Biometric Systems: Most current studies on adaptive biometric systems focus on small to medium-sized datasets with around 33 to 550 users[29]. However, in real-world applications like border control, the number of users can be significantly larger. Scaling these systems raises concerns regarding the time and resources required for adaptation. While small datasets are useful for proof of concept, larger datasets are crucial for evaluating the true capabilities and limitations of adaptive systems. Future research needs to explore how large-scale datasets affect adaptation strategies in real-time systems.

Acquisition of Suitable Datasets: One of the most pressing issues in the field is the lack of large and varied biometric datasets that can be used to evaluate adaptive biometric systems. To properly assess the adaptability of these systems, datasets should include multiple samples per user, ideally collected over different sessions under varying conditions. However, publicly available datasets often lack such variety, making it challenging to evaluate the performance of systems in real-world settings. Gathering long-term data for adaptive systems is time-consuming, but it is critical to improving the accuracy and resilience of biometric recognition technologies.

Generation of Synthetic Datasets: Since collecting real biometric data over long periods is difficult, generating synthetic datasets has become a popular alternative. These datasets can simulate temporal changes in biometric features, allowing researchers to test algorithms on large-scale data. Recent work has explored this approach for various modalities, including fingerprint and keystroke dynamics. However, challenges remain in accurately simulating real-world biometric variations, especially as changes differ across modalities. Future research should focus on modelling how temporal changes affect different biometric features to enhance synthetic dataset realism.

Attacks on Biometric Systems: A significant threat to adaptive biometric systems comes from attacks such as spoofing, replay, and poisoning attacks. Poisoning attacks occur when adversaries intentionally introduce false data into the system, leading to the corruption of genuine biometric templates. Adaptive systems, which update their templates over time, are particularly vulnerable to such attacks because they can mistakenly incorporate malicious data as legitimate input. Countermeasures like liveness detection and ensemble techniques can help mitigate these vulnerabilities. Nonetheless, adaptive

biometric systems must balance between adaptability and security to avoid being exploited by adversaries.

Adaptation to Both Temporal and Environmental Conditions: Biometric systems must adapt not only to temporal changes, such as ageing but also to varying acquisition conditions. For example, in facial recognition systems, templates may need to adapt to different lighting or facial poses. Systems like Self-Update can adapt over time, while others like Sliding Window are better suited for adapting to changing conditions. A key challenge is designing systems that can adapt to both types of changes without compromising performance.

Commercial Applications of Adaptive Biometric Systems: While the potential benefits of adaptive biometric systems are well-documented, few commercial applications have implemented these strategies. For instance, Apple's Face ID uses adaptive methods to improve face data over time, but many other systems remain static. One of the major challenges in commercial adoption is the vulnerability of adaptive systems to attacks, which could undermine user trust. To encourage wider adoption, developers must implement robust security measures to prevent attackers from corrupting biometric templates during the adaptation process.

Adaptive Biometrics in Mobile Applications: Mobile devices present unique challenges for biometric systems due to limited computational resources and storage. However, by offloading processing tasks to cloud servers, adaptive biometric systems could be effectively implemented on mobile platforms. Ensuring a secure communication channel for transmitting biometric data between mobile devices and cloud servers is essential. Future research should also focus on gathering long-term sensor data from mobile devices to improve adaptive biometric models on mobile platforms.

7. Conclusion

Adaptive biometric systems represent a significant step forward in authentication technology, allowing dynamic adaptation of biometric templates according to changes in users and their working conditions. Unlike traditional biometric systems, whose performance degrades over time due to natural changes in users, adaptive systems offer mechanisms to continuously update templates. This allows the systems to maintain high accuracy and security, even in complex scenarios.

One of the key benefits of these systems is their ability to minimize mismatch errors caused by user variations, such as ageing, posing changes, or acquisition conditions. This improves system accuracy and reduces the need for users to re-enrol, which in turn lowers maintenance costs. Additionally, adaptive biometric systems provide flexibility, which is particularly important for commercial applications where acquisition conditions often change.

However, despite the many advantages, these systems face significant challenges, particularly regarding security and privacy. One of the major threats is poisoning attacks, where malicious users introduce false data into the system, potentially compromising the biometric templates. Since adaptive systems continuously update their templates, they are particularly vulnerable to such attacks. This calls for the development of new protective measures, such as liveness detection mechanisms or the use of multimodal systems to enhance security.

Another open challenge in this field is managing large-scale datasets and system adaptation to them. Most research so far has focused on small user groups, while real-world applications, such as border control, require systems capable of handling thousands of users. In the future, there will be a need to develop systems that can adapt to large-scale datasets while maintaining efficiency.

A significant challenge is also the collection of appropriate datasets for evaluating adaptive biometric systems. The datasets need to include multiple samples per user, collected across different sessions and conditions, to allow for realistic system evaluations. However, such data is difficult to obtain, and collecting it is expensive and time-consuming. As an alternative, generating synthetic datasets is being considered, allowing for testing adaptive algorithms in simulated conditions. This approach is promising, but challenges remain in accurately simulating real-world biometric changes.

In the future, research should focus on the development of adaptive systems for mobile devices, where computational and storage resources are limited. Offloading data processing to the cloud is one way to address this issue, though secure communication channels for transmitting biometric data

between mobile devices and cloud servers remain a challenge. Moreover, long-term data collection from mobile sensors is crucial for improving adaptive models in mobile platforms.

In conclusion, adaptive biometric systems are a new and significant technology offering solutions to many limitations of traditional systems. However, to enable broader adoption, current challenges related to security, data management, and adaptation to new conditions must be addressed.

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