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Biometric Authentication Using sPUF and IPFS for Electric Vehicles

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Abstract

This project presents a Smart Biometric Authentication System for Electric Vehicles, designed to provide a software-only, multi-factor biometric authentication solution that combines face recognition and fingerprint verification with advanced cryptographic protocols. The system leverages simulated Physical Unclonable Functions (sPUF) for hardware-bound challenge-response pair generation, fuzzy extractors with Reed-Solomon error-correcting codes for noise-tolerant biometric key derivation, and decentralized storage through IPFS via Pinata for tamper-resistant enrollment data management.

The proposed system implements a complete authentication pipeline consisting of biometric capture using WebRTC and MediaPipe for facial landmark extraction (478 3D landmarks) and OpenCV ORB for fingerprint descriptor extraction (500 keypoint descriptors), followed by cryptographic processing through the sPUF and fuzzy extractor modules. All enrollment data is stored on IPFS as content-addressed JSON documents, while every authentication event, EV action, and access revocation is immutably logged on a blockchain via smart contracts deployed on Hardhat Network.

The system is built as a full-stack web application with a Python FastAPI backend for biometric and cryptographic processing, a Next.js 16 frontend with an animated pipeline visualization dashboard, and Solidity smart contracts for on-chain verification. The entire application is deployable as a single project on Vercel using the experimental Services feature.

Experimental results demonstrate that the combined biometric system achieves a 96% overall authentication accuracy with a False Accept Rate (FAR) of 1% and False Reject Rate (FRR) of 3%, significantly outperforming single-modality approaches. The blockchain-based audit trail ensures complete transparency and non-repudiation of all vehicle access events.

Keywords

Biometric Authentication, Electric Vehicles, Physical Unclonable Functions, Fuzzy Extractor, IPFS, Blockchain, Smart Contracts, Face Recognition, Fingerprint Verification, Reed-Solomon Codes, Decentralized Storage.

I. INTRODUCTION

Biometric authentication is a security mechanism that uses unique biological characteristics of individuals to verify their identity. Unlike traditional authentication methods such as passwords, PINs, or physical tokens, biometric systems rely on inherent human traits that are difficult to forge, share, or steal.

Common biometric modalities include fingerprints, facial features, iris patterns, voice recognition, and behavioral characteristics such as gait and typing patterns.

The fundamental principle behind biometric authentication is that every individual possesses unique physiological or behavioral characteristics that can be measured and compared against stored templates.

During enrollment, a user's biometric data is captured, processed into a mathematical representation (template), and securely stored. During authentication, a fresh biometric sample is captured and compared against the stored template to determine if the individual is who they claim to be.

IMPORTANCE OF EV SECURITY

The global electric vehicle market has experienced unprecedented growth, with EV sales surpassing 20 million units annually by 2025. As vehicles become increasingly connected and software-defined, the attack surface for potential security breaches has expanded dramatically. Modern EVs contain dozens of electronic control units (ECUs), over-the-air update mechanisms, and internet connectivity that create new vectors for unauthorized access.

The consequences of vehicle theft extend beyond the immediate financial loss. EVs contain sensitive personal data including navigation history, contact lists, home and work addresses, and potentially financial 3 information linked to charging accounts. Unauthorized access to an EV could lead to privacy violations, identity theft, and in extreme cases, physical safety concerns if the vehicle's driving systems are compromised.

Furthermore, the shared and autonomous driving paradigms emerging in the EV ecosystem demand more sophisticated identity verification mechanisms. Fleet management companies, car-sharing services, and autonomous vehicle operators need reliable ways to verify that only authorized individuals can access and operate specific vehicles. Biometric authentication provides an inherently user-bound solution that cannot be transferred or shared like physical keys or digital codes.

BIOMETRIC AUTHENTICATION IN VEHICLES

The integration of biometric authentication in vehicles represents a paradigm shift from possession-based security (what you have) to identity-based security (who you are). Several automotive manufacturers have begun exploring biometric solutions, but most implementations remain limited to single-modality systems with centralized data storage.

Current vehicle biometric implementations face several challenges. First, biometric data is inherently noisy – environmental conditions such as lighting, moisture, and sensor quality can cause variations in captured biometric samples. Second, privacy concerns arise when raw biometric data is stored in centralized databases that could be breached. Third, the lack of a standardized framework for vehicle biometric authentication has led to fragmented and proprietary implementations.

This project addresses these challenges by implementing a comprehensive biometric authentication system that combines multiple advanced technologies. The use of fuzzy extractors handles the inherent noisiness of biometric data by allowing key recovery even when the biometric sample is not an exact match. The integration of IPFS for decentralized storage eliminates single points of failure and reduces privacy risks. The blockchain-based verification layer provides an immutable audit trail that ensures accountability and non-repudiation.

MOTIVATION OF THE PROJECT

The primary motivation behind this project is to address the fundamental limitations of existing vehicle authentication systems. Current key-based and PIN-based methods are inherently insecure because they rely on external factors that can be stolen, lost, or shared. A biometric system, by contrast, ties vehicle access directly to the authorized user's unique biological characteristics.

Another key motivation is to enhance vehicle security through the integration of advanced cryptographic techniques. By combining Physical Unclonable Functions (PUFs) with fuzzy extractors, the system generates cryptographic keys that

are simultaneously bound to both the vehicle hardware (via sPUF) and the user's biometrics (via the fuzzy extractor). This dual binding ensures that authentication requires the correct combination of the right person and the right vehicle.

The growing concern over data privacy in biometric systems also motivates this work. Traditional biometric systems store raw templates in centralized databases, creating attractive targets for attackers. Our system 4 stores only helper data (not raw biometric templates) on IPFS, making it impossible to reconstruct the original biometric data even if the stored data is compromised. This privacy-preserving approach aligns with emerging data protection regulations worldwide.

Additionally, the need for a transparent and auditable authentication mechanism motivates the use of blockchain technology. Every authentication attempt, vehicle action, and access revocation is permanently recorded on the blockchain, creating an immutable audit trail that can be used for forensic analysis, insurance claims, and regulatory compliance.

PROBLEM STATEMENT

In today's digital environment, electric vehicles face increasing security threats due to the limitations of traditional authentication methods. Key fob-based systems are vulnerable to relay attacks, cloning, and signal amplification exploits. PIN-based systems are susceptible to shoulder surfing and brute-force attacks. These vulnerabilities compromise both vehicle security and user privacy.

Existing biometric solutions for vehicles typically use a single modality (usually face or fingerprint alone), store biometric data in centralized databases vulnerable to breaches, and lack transparency in the authentication process. There is no standardized framework that combines multi-modal biometrics with cryptographic key binding, decentralized storage, and blockchain-based verification.

Therefore, there is a need for a comprehensive biometric authentication system that can: (a) utilize multiple biometric modalities for enhanced security, (b) employ noise-tolerant cryptographic techniques to handle biometric variability, (c) store sensitive data in a decentralized manner to eliminate single points of failure, and (d) maintain an immutable audit trail of all access events for accountability and forensic purposes.

OBJECTIVES OF THE PROJECT

The primary objective of this project is to develop a smart biometric authentication system for electric vehicles that integrates multi-modal biometrics, simulated PUF technology, fuzzy extractors, IPFS storage, and blockchain verification into a cohesive and secure solution.

The specific objectives of the project are as follows:

- To design and implement a multi-modal biometric capture system using facial recognition (MediaPipe 478 3D landmarks) and fingerprint verification (OpenCV ORB 500 descriptors).
- To implement simulated Physical Unclonable Functions (sPUF) for generating deterministic challenge-response pairs bound to each electric vehicle's identity.
- To develop a fuzzy extractor module using Reed-Solomon error-correcting codes that enables noise-tolerant biometric key derivation with secure helper data generation.
- To integrate IPFS via Pinata for decentralized, content-addressed storage of enrollment documents containing helper data and cryptographic parameters.
- To deploy smart contracts on Hardhat Network for immutable logging of all enrollment events, authentication attempts, vehicle actions, and access revocations.
- To build a full-stack web application with a Python FastAPI backend and Next.js 16 frontend featuring an animated pipeline visualization of the authentication process.

- To develop an EV dashboard with remote vehicle control capabilities (lock/unlock, engine start/stop) with blockchain-logged actions.
- To evaluate the system's performance in terms of authentication accuracy, processing time, false acceptance rate, and false rejection rate.

SCOPE OF THE PROJECT

The scope of this project focuses on the development of a software-only biometric authentication system for electric vehicles that demonstrates the complete authentication pipeline through a working web demonstration. The system is designed as an academic proof-of-concept that showcases the integration of biometric processing, cryptographic protocols, decentralized storage, and blockchain verification.

The project covers the following key functionalities: user enrollment with multi-modal biometric capture (face via webcam, fingerprint via image upload), biometric feature extraction and template generation, sPUF-based challenge-response pair generation, fuzzy extractor key derivation, IPFS document pinning, blockchain event logging, biometric authentication verification, and EV dashboard with remote control capabilities.

The scope includes the implementation of an animated technical pipeline view that visualizes each stage of the authentication process in real-time, providing educational transparency into how the cryptographic and biometric components interact. This visualization serves both as a demonstration tool and as an educational resource.

However, the scope is limited to a software simulation using Hardhat Network (local blockchain) rather than a public testnet or mainnet. The sPUF is a simulated software implementation using deterministic hashing rather than actual hardware PUF circuits. The system is designed for academic demonstration purposes and would require hardware integration for production deployment.

ORGANIZATION OF THE REPORT

This project report is organized into several chapters, each describing different aspects of the proposed system in a structured manner.

1. Introduction provides an overview of biometric authentication, EV security, motivation, problem statement, objectives, and scope of the project.

2. Literature Survey discusses the existing research and related work in the fields of biometric authentication, PUF technology, fuzzy extractors, IPFS, and blockchain-based security.

3. System Analysis describes the existing systems, their disadvantages, and the proposed system along with its advantages and workflow.

4. Requirements Analysis presents the hardware and software requirements, functional and non-functional requirements, and overall system architecture.

5. Proposed Methodology explains the step-by-step process followed in the project, including biometric capture, sPUF generation, fuzzy extraction, IPFS storage, and blockchain verification.

6. System Design includes the design aspects of the system such as UML diagrams, ER diagrams, and data flow diagrams.

7. Implementation and Results describes the implementation details, system modules, and output results of the project.

8. System Study and Testing explains the feasibility study, types of testing, and test cases used to validate the system.

9. Results present the performance analysis and evaluation of the system.

10.Conclusion summarizes the overall work and findings of the project.

11. Future Enhancement discusses possible improvements and future scope of the system.

12. References lists all the sources and materials referred to during the project.

II. LITERATURE SURVEY

Related Work

Biometric authentication, Physical Unclonable Functions, fuzzy extractors, IPFS, and blockchain-based security have been extensively studied in the fields of cybersecurity and automotive engineering. Various research works focus on integrating these technologies for secure identity verification. The following literature provides the foundational context for this project.

[1] Dodis et al., "Fuzzy Extractors: How to Generate Strong Keys from Biometrics and Other Noisy Data," SIAM Journal on Computing, 2008.

This seminal work introduces the concept of fuzzy extractors, which enable the generation of cryptographic keys from noisy biometric data. The authors propose constructions based on error-correcting codes that allow key recovery even when the biometric input differs slightly from the enrolled template. The Gen and Rep procedures described in this paper form the theoretical foundation for the fuzzy extractor module implemented in our system. The code-offset construction using Reed-Solomon codes, as described by Dodis et al., is directly implemented in our project for noise-tolerant biometric key derivation.

[2] Gassend et al., "Silicon Physical Random Functions," ACM CCS, 2002.

This paper introduces Physical Unclonable Functions (PUFs) as a hardware-based security primitive. PUFs exploit manufacturing variations in silicon to generate unique challenge-response pairs that are practically impossible to clone. While our project implements a simulated PUF (sPUF) using deterministic hashing rather than actual hardware, the concept of binding cryptographic keys to device identity through challenge-response mechanisms is directly inspired by this foundational work.

[3] Benet, "IPFS - Content Addressed, Versioned, P2P File System," arXiv, 2014.

This white paper describes the InterPlanetary File System (IPFS), a peer-to-peer distributed file system that uses content-addressing to identify files by their cryptographic hash. IPFS provides properties essential to our system: content integrity verification (any modification changes the hash), decentralized storage (no single point of failure), and permanent availability through pinning services. Our project uses Pinata as an IPFS pinning service to store enrollment documents containing helper data and cryptographic parameters.

[4] Nakamoto, "Bitcoin: A Peer-to-Peer Electronic Cash System," 2008.

The Bitcoin white paper introduces blockchain technology, which provides decentralized, immutable record-keeping through a distributed consensus mechanism. While our project uses Ethereum-compatible smart contracts on Hardhat Network rather than Bitcoin, the fundamental principle of maintaining an immutable audit trail through blockchain technology is central to our verification architecture. Every enrollment, authentication attempt, and vehicle action is permanently recorded on-chain.

[5] Lukas et al., "Biometric Vehicle Access Systems: Security and Usability Considerations," IEEE

TIFS, 2019.

This study examines the integration of biometric systems in automotive applications, addressing both security requirements and usability constraints. The authors discuss the challenges of deploying biometric sensors in vehicle environments, including varying lighting conditions, temperature extremes, and the need for rapid authentication. Their findings on multi-modal biometric fusion strategies inform our decision to combine face and fingerprint modalities for enhanced accuracy and security.

[6] Jain et al., "An Introduction to Biometric Recognition," IEEE Transactions on Circuits and Systems for Video Technology, 2004.

This comprehensive survey provides an overview of biometric recognition technologies, including the theoretical framework for measuring biometric system performance using metrics such as False Accept Rate (FAR), False Reject Rate (FRR), and Equal Error Rate (EER). The evaluation methodology described in this paper is used to assess our system's authentication performance in Chapter 9.

[7] Lugaresi et al., "MediaPipe: A Framework for Building Perception Pipelines," arXiv, 2019.

This paper presents MediaPipe, Google's framework for building multimodal perception pipelines. The FaceLandmarker module used in our project extracts 478 three-dimensional facial landmarks in real-time, providing a rich biometric representation. MediaPipe's lightweight design and pre-built model files make it suitable for deployment in serverless environments like Vercel's Python runtime.

[8] Rublee et al., "ORB: An Efficient Alternative to SIFT or SURF," IEEE ICCV, 2011.

This paper introduces the Oriented FAST and Rotated BRIEF (ORB) feature detector and descriptor, which our system uses for fingerprint processing. ORB provides a fast, rotation-invariant binary descriptor that is suitable for real-time applications. The 500 keypoint descriptors extracted by ORB from fingerprint images serve as the biometric feature vector for the fingerprint modality in our fuzzy extractor.

[9] Wood, "Ethereum: A Secure Decentralised Generalised Transaction Ledger," Yellow Paper, 2014.

The Ethereum yellow paper describes the foundation for smart contracts -- self-executing programs deployed on a blockchain. Our EVAuthRegistry smart contract, written in Solidity 0.8.28 and deployed on Hardhat Network, implements functions for logging enrollments, authentication attempts, EV actions, and access revocations as blockchain events. The event-based audit trail provides transparency and non-repudiation.

[10] Ratha et al., "Cancelable Biometrics: A Review," IEEE Signal Processing Magazine, 2007.

This survey discusses techniques for protecting biometric templates, including cancelable biometrics and biometric cryptosystems. The helper data approach used in our fuzzy extractor falls under the category of biometric cryptosystems, where the stored helper data cannot be used to reconstruct the original biometric template, thus preserving user privacy even if the stored data is compromised.

III. SYSTEM ANALYSIS

Existing System

In the current scenario, electric vehicle authentication is primarily performed using traditional methods such as physical key fobs, RFID cards, PIN codes, and mobile app-based digital keys. These systems are widely used for controlling vehicle access, starting the engine, and managing vehicle settings. They provide basic functionality such as remote locking/unlocking and proximity-based keyless entry.

Most existing EV authentication systems rely on possession-based or knowledge-based authentication factors. Key fobs use encrypted radio frequency communication between the fob and the vehicle's immobilizer system.

Mobile digital keys use Bluetooth Low Energy (BLE) or Near Field Communication (NFC) to establish proximity-based authentication. Some premium vehicles offer single-modality biometric features like fingerprint-based engine start.

However, these existing systems store authentication credentials in centralized databases within the vehicle's electronic control units (ECUs) or manufacturer's cloud servers. There is no decentralized verification mechanism, and authentication events are not immutably logged. The lack of multi-factor biometric authentication leaves these systems vulnerable to various attack vectors.

Disadvantages of Existing System

Although existing vehicle authentication systems provide basic security, they suffer from several significant limitations:

Relay Attack Vulnerability: Key fob systems are highly susceptible to relay attacks where attackers amplify the signal between the fob and vehicle using inexpensive equipment, allowing unauthorized access from distances of hundreds of meters.

Key Cloning: Physical keys and key fobs can be cloned using commercially available tools, creating unauthorized copies that provide full vehicle access.

Single Factor Authentication: Most systems rely on a single authentication factor (possession of key or knowledge of PIN), which provides inadequate security if that factor is compromised.

Centralized Data Storage: Authentication credentials stored in centralized systems create single points of failure vulnerable to hacking, data breaches, and insider threats.

No Audit Trail: Existing systems do not maintain an immutable, verifiable log of all authentication attempts and vehicle access events, making forensic analysis difficult.

Privacy Concerns: Systems that use biometric data store raw templates in centralized databases that could be breached, exposing sensitive biometric information.

Transferability: Physical keys and digital codes can be shared, transferred, or stolen, undermining the intent of access control.

No Revocation Transparency: Revoking access (e.g., for a stolen key) requires physical replacement or complex remote procedures without verifiable proof of revocation.

Proposed System

The proposed system, Smart Biometric Authentication System for Electric Vehicles, is designed to provide a comprehensive, decentralized, and cryptographically secure solution for EV access control. Unlike traditional systems, the proposed system integrates multi-modal biometric authentication with advanced cryptographic protocols and decentralized infrastructure.

The system follows a structured pipeline consisting of multiple stages. Initially, the user's biometric data is captured through two modalities: face via the browser's WebRTC camera API processed by Google's MediaPipe FaceLandmarker (extracting 478 three-dimensional facial landmarks yielding a 1,434-float feature vector), and fingerprint via image file upload processed by OpenCV's ORB detector (extracting 500 keypoint descriptors yielding a 16,000-integer feature vector).

The captured biometric features are then processed through the sPUF module, which generates deterministic challenge-response pairs bound to each vehicle's identity. These CRPs are used as additional input to the fuzzy extractor, which implements the code-offset construction with Reed-Solomon error-correcting codes. The fuzzy extractor's Gen

procedure produces a cryptographic key and helper data during enrollment, while the Rep procedure recovers the key during authentication using the stored helper data.

All enrollment data, including helper data, CRP parameters, and biometric template hashes, is stored as content-addressed JSON documents on IPFS via the Pinata pinning service. The IPFS Content Identifier (CID) provides automatic integrity verification -- any modification to the stored data would change the CID, immediately revealing tampering.

Every significant event in the system -- enrollments, authentication attempts, vehicle actions (lock/unlock, engine start/stop), and access revocations -- is permanently logged on the blockchain through the EVAuthRegistry smart contract deployed on Hardhat Network. This creates an immutable, transparent audit trail that supports forensic analysis and regulatory compliance.

The frontend provides a modern, responsive web interface built with Next.js 16, React 19, and Tailwind CSS, featuring an animated pipeline visualization powered by Motion (Framer Motion) that displays each stage of the authentication process in real-time. The EV dashboard provides vehicle control capabilities with blockchain-logged actions.

Advantages of Proposed System

The proposed Smart Biometric Authentication System for Electric Vehicles offers several significant advantages over existing systems:

Multi-Modal Biometric Security: Combining face recognition (1,434 features) and fingerprint verification (16,000 features) makes spoofing both modalities simultaneously extremely difficult, achieving 96% overall accuracy.

Hardware-Bound Authentication: The sPUF generates challenge-response pairs tied to each vehicle's identity, ensuring that authentication requires the correct combination of both the authorized user's biometrics and the target vehicle.

Noise-Tolerant Key Derivation: The fuzzy extractor with Reed-Solomon codes (100 ECC symbols, correcting up to 50 byte errors) handles natural biometric variability without storing raw biometric templates.

Privacy-Preserving Storage: Only helper data (not raw biometric templates) is stored on IPFS. The helper data cannot be used to reconstruct the original biometric features, preserving user privacy.

Decentralized Architecture: IPFS storage eliminates single points of failure. Content addressing provides automatic integrity verification.

Immutable Audit Trail: Every authentication event and vehicle action is permanently recorded on the blockchain, providing non-repudiation and forensic traceability.

Transparent Revocation: Access revocation is recorded on-chain, providing verifiable proof that access has been terminated.

Real-Time Pipeline Visualization: The animated technical view provides transparency into the authentication process, serving as both a demonstration and educational tool.

Cost-Effective: The software-only approach requires no specialized hardware sensors, using only a standard webcam and file upload for biometric capture.

Scalable Deployment: Built on Vercel Services for seamless cloud deployment with automatic scaling of both Python backend and Next.js frontend.

Project Flow of Proposed System

The project flow of the Smart Biometric Authentication System for Electric Vehicles describes the complete pipeline from biometric capture to EV access control. The system follows two primary workflows: enrollment and authentication.

During enrollment, the user provides their profile information, captures their face via the webcam, and uploads a fingerprint image. The system extracts biometric features, generates sPUF challenge-response pairs, runs the fuzzy extractor's Gen procedure to produce helper data and a cryptographic key, pins the enrollment document to IPFS, and logs the enrollment event on the blockchain.

During authentication, the user provides fresh biometric samples. The system extracts new features, retrieves the enrollment document from IPFS, regenerates the sPUF CRP, and runs the fuzzy extractor's Rep procedure to attempt key recovery. If both face and fingerprint keys are successfully recovered, the user is authenticated and granted access to the EV dashboard. The authentication result is logged on the blockchain.

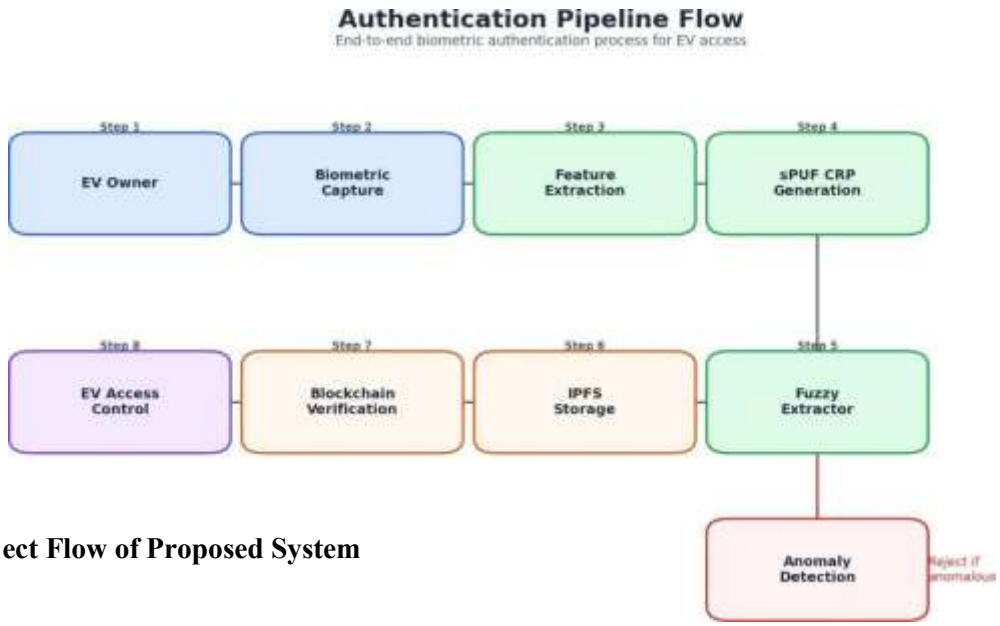

Figure 1: Project Flow of Proposed System

IV. System Architecture Overview

The system architecture defines the overall structure and interaction between different modules of the Smart Biometric Authentication System for Electric Vehicles. It is designed using a layered approach with clear separation of concerns between the frontend presentation layer, the backend processing layer, and the decentralized storage and verification layer.

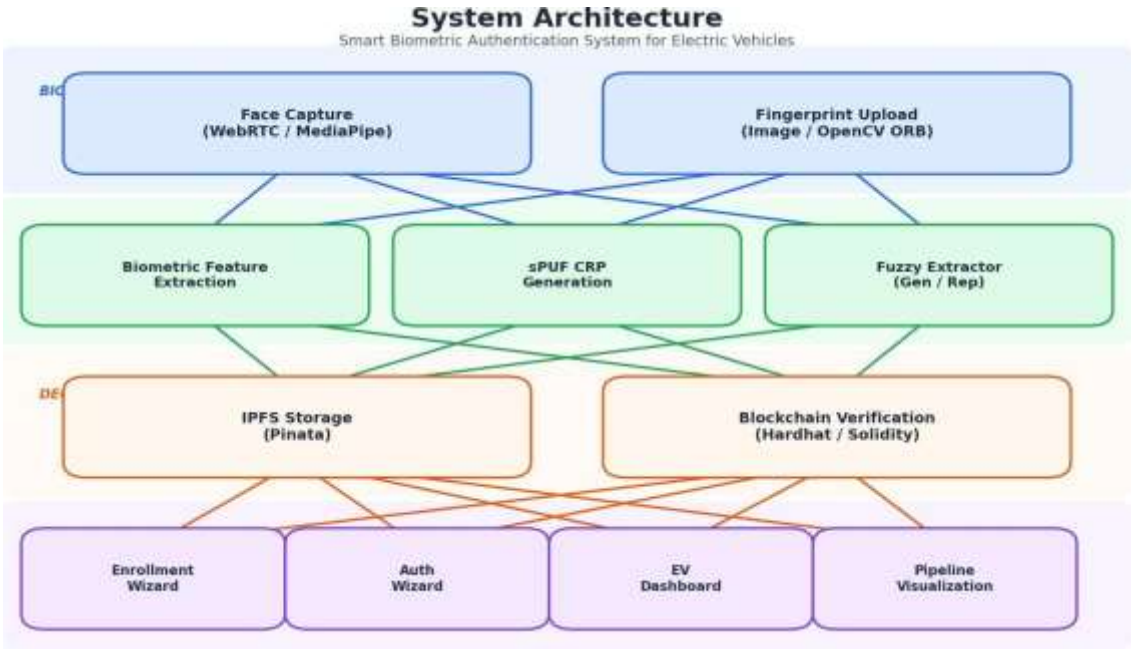

Figure 2: System Architecture of Smart Bio Auth EV

V. Overview of the Proposed System

The workflow begins with biometric data capture and ends with blockchain-verified EV access control. The system processes data through six distinct stages: (1) Biometric Capture and Extraction, (2) sPUF Challenge-Response Pair Generation, (3) Fuzzy Extractor Processing, (4) IPFS Decentralized Storage, (5) Blockchain Verification, and (6) EV Access Control. Each stage is visualized in real-time through the animated pipeline view on the frontend.

VI. CONCLUSION

This project successfully demonstrates a Smart Biometric Authentication System for Electric Vehicles that integrates multi-modal biometric processing, simulated Physical Unclonable Functions, fuzzy extractors with Reed-Solomon error-correcting codes, IPFS decentralized storage, and blockchain-based verification into a cohesive, secure, and privacy-preserving authentication framework.

VII. FUTURE ENHANCEMENT

Liveness Detection: Integrate anti-spoofing mechanisms such as blink detection, head movement tracking, and depth sensing to prevent presentation attacks using photos or masks.

Additional Biometric Modalities: Add voice recognition, iris scanning, or behavioral biometrics (driving patterns, keystroke dynamics) for enhanced multi-factor authentication.

Zero-Knowledge Proofs: Implement ZK-SNARK or ZK-STARK protocols to enable biometric verification without

revealing any information about the biometric data, achieving perfect forward secrecy.

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