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Blockchain For Decentralized Identity Management With Biometrics And Access Token

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Abstract– This research addresses the critical vulnerabilities inherent in centralized identity management systems, which are susceptible to single points of failure, data breaches, and profound privacy violations. To mitigate these risks, we propose and detail the architectural design of a novel, decentralized identity framework that integrates blockchain technology with biometric authentication and advanced cryptographic principles.

The proposed methodology generates a unique, blockchain-based identity for each user by cryptographically hashing personal data and biometric templates (fingerprint and facial recognition) using SHA-256. Identity verification for service providers is facilitated by access tokens issued via smart contracts, which allow for authentication without direct access to sensitive biometric data. The system enforces secure access by validating tokens against real-time biometric verification, with automatic revocation upon mismatch.

The framework incorporates a Zero-Knowledge Proof (ZKP) mechanism to enable privacy-preserving verification, allowing users to authenticate their identity while withholding the underlying data. Decentralized storage of hashed biometric templates is achieved through integration with the Internet Computer Protocol (ICP), thereby eliminating centralized points of failure. The system's performance is rigorously evaluated using key metrics, including the False Acceptance Rate (FAR), False Rejection Rate (FRR), token generation latency, and blockchain transaction throughput.

This work's primary contribution is the development of a resilient, interoperable, and privacy-centric model for digital identity. The results demonstrate enhanced security and a reduced risk of identity theft, positioning this solution as a secure and scalable alternative to traditional centralized identity infrastructures.

Keywords: Decentralized Identity, Blockchain, Biometric Authentication, Zero-Knowledge Proof, Internet Computer Protocol (ICP)

1. INTRODUCTION

In this section introduction of the study, the background of the study, the problem statement, the objectives of the study, the scope and limitation of the research, and the significance of the study are all outlined.

1.1 Introduction

The contemporary digital ecosystem is increasingly defined by the vulnerabilities of centralized identity management systems, which have become prime targets for malicious actors. These systems, whether operated by governments or corporations, are built on an architecture that concentrates vast amounts of personally identifiable information (PII) into single, high-value repositories. This structural flaw has resulted in a global epidemic of data breaches, compromising millions of records and costing billions of dollars annually [1]. For instance, a recent study highlighted a significant increase in cyberattacks targeting national identity databases, leading to widespread identity theft and fraud [2] .The catastrophic failure of a single centralized system can have cascading effects, leading to a profound erosion of public trust in digital services and institutional data stewardship.

This centralized model also fundamentally undermines user privacy and sovereignty. Individuals are forced to surrender control over their data, creating an imbalance of power where third parties dictate how personal information is stored, processed, and monetized [3] . This paradigm is antithetical to the principles of Self-Sovereign Identity (SSI), which advocates for a user-centric model where individuals own and control their digital identity [4]. The need for a more equitable and secure alternative is underscored by global privacy regulations like GDPR, which emphasize user consent and data minimization, principles that are often difficult to enforce within traditional centralized frameworks [5].

Blockchain technology has emerged as a disruptive and promising solution to these challenges. Its decentralized, immutable ledger and robust cryptographic security provide a trustless foundation where identity records cannot be tampered with or unilaterally controlled by a single entity. The use of blockchain enables the creation of decentralized identifiers (DIDs) and verifiable credentials (VCs), allowing users to prove their identity attributes without relying on a central authority or revealing unnecessary information [6], [7] . This shift from a central-trust model to a distributed-trust model is a cornerstone of next-generation identity frameworks.

While blockchain provides the foundation, robust authentication is critical for preventing unauthorized access. Biometric authentication offers a highly secure and convenient method, utilizing unique physiological or behavioral traits for verification. However, the traditional use of biometrics has been fraught with privacy risks, as storing raw biometric data in any database, even a decentralized one, creates an irreversible vulnerability if compromised. This research addresses this by employing a privacy-preserving approach where biometric templates are processed locally on the user's device and transformed into a non-reversible hash using SHA-256. Only this hash is used for verification, ensuring that the raw biometric data never leaves the user's control, thereby mitigating the risk of exposure and misuse [8].

The system further enhances privacy and security through the integration of advanced cryptographic and decentralized technologies. Zero-Knowledge Proof (ZKP) is incorporated to enable verifiable, privacy-preserving authentication, allowing users to prove a claim (e.g., "I am over 18") without revealing the underlying data [9], [10]. This capability is crucial for adhering to the principle of data minimization. Furthermore, the Internet Computer Protocol (ICP) serves as a decentralized storage solution for the hashed biometric templates, ensuring that the entire system remains free from centralized points of failure, a critical improvement over systems that might still rely on centralized storage for certain components [11], [12]. The convergence of these technologies provides a comprehensive and resilient framework that is the focus of this study.

1.2 Problem statement

In today's increasingly digital world, identity management is crucial for accessing essential services such as healthcare, banking, education, and governmental functions. Conventional identity management systems predominantly rely on centralized databases controlled by governmental or institutional authorities. These centralized systems present multiple critical challenges that undermine security, privacy, and user autonomy [13].

The fundamental issue is that this reliance on central hubs creates a critical and unacceptable vulnerability. When a single database holds the sensitive identities of millions, it becomes a high-value, attractive target for cybercriminals [1], [3]. The financial and reputational damage from such large-scale data breaches is immense, with recent reports detailing the global average cost of a data breach at over $4 million [14], [15]. This is not an isolated problem, as [16]. and Younus et al. (2023) have shown that these security failures have become a systemic issue across global identity systems. The result is a cycle of catastrophic data loss, widespread identity theft, and a profound erosion of public trust in the institutions entrusted with our most sensitive information [17], [18].

Beyond these security failures, the centralized model strips individuals of their fundamental right to control their own data [4], [19]. Users are forced to hand over their personally identifiable information to third parties, creating a power imbalance that often leads to privacy violations and the unauthorized use of personal data for commercial purposes [5], [18]. This lack of data sovereignty stands in direct conflict with modern principles of digital privacy and highlights a growing demand for a more user-centric, self-governed identity model [3], [4]. The challenge of reconciling centralized data management with increasingly stringent regulations, such as GDPR and CCPA, further underscores the urgent need for a new architectural paradigm [2], [5].

While blockchain technology has emerged as a promising foundation for a decentralized approach, existing solutions often fall short of providing a complete and secure framework. Many of these solutions, as noted by [6] and [9], struggle with a lack of a robust, privacy-preserving biometric authentication mechanism, a critical layer for preventing credential theft and ensuring convenient user experience [8]. Additionally, the storage of biometric data, even in a hashed form, requires a truly decentralized infrastructure to avoid simply replacing one central point of failure with another, a challenge that [12] and [11] have explored. The absence of a holistic system that seamlessly combines these advanced security and privacy features is a significant unresolved challenge in the field [8], [10]..

1.3 Research Objectives

1.3.1 General Objective

The general objective of this thesis is to design and develop a blockchain for decentralized identity management with biometrics and access token.

1.3.2 Specific objectives

i. To Design a decentralized identity system's architecture and implement a unique, verifiable identity layer using cryptographic hashing of personal and biometric data.

ii. To implement a unique, verifiable identity layer on a blockchain, where user identities are created by cryptographically hashing personal data and biometric templates using the SHA-256 algorithm

iii. To Develop a secure authentication mechanism with smart contracts for token management, enabling service providers to verify identities without direct access to sensitive data.

iv. To Integrate a Zero-Knowledge Proof (ZKP) mechanism to allow users to prove identity attributes while revealing minimal personal information during verification.

II LITERATURE REVIEW

2.1 Introduction

This chapter critically reviews the existing body of knowledge pertinent to decentralized identity management, blockchain technology, biometric authentication, and advanced cryptographic principles, including Zero-Knowledge Proofs (ZKP). It systematically surveys current research, identifies prevailing challenges within traditional identity systems, and highlights the potential of emerging technologies to address these issues. The aim is to establish the current state-of-the-art, pinpoint significant research gaps, and contextualize the novel contributions of this study within the broader academic and technological landscape.

2.2 Empirical review

The world of academia has done a lot to explore the rich facets of decentralized solutions within the digital identity realmisms. This review then links all key research papers by identifying their core problems and by highlighting their limitations. It then sets the context and justification for the novel frame proposed in the present research.

Based on the surveys by [20] and [13], there's a clear gap in the existing research on decentralized identity systems. The Younus et al. survey effectively categorizes the vulnerabilities of both centralized and decentralized identity paradigms but falls short by not proposing or implementing a practical solution, remaining a theoretical discussion. Similarly, the Gupta et al. paper highlights the role of blockchain in addressing the security and privacy issues of traditional models by reviewing existing solutions. However, it also fails to propose a novel, integrated architectural framework, instead emphasizing the need for one. Both papers identify the shortcomings of current models and the need for a practical, cohesive system that integrates various technologies.and this is a gap that this research aims to fill.

In the research by [3] and [6], there's a recurring theme of theoretical approaches lacking practical implementation and empirical evaluation in the field of decentralized identity systems. The [3]. review, while comprehensive in its analysis of conceptual models and existing systems, fails to provide any practical solutions to the identified limitations regarding performance and scalability. Similarly, the [6]. paper proposes a theoretical framework for decentralized identity using verifiable credentials but overlooks the crucial component of a solid biometric authentication layer. This omission leaves the system vulnerable to credential theft and social engineering. Furthermore, the lack of a detailed implementation or performance analysis in their work makes it difficult to assess the real-world viability of their proposed architecture. Both studies highlight a significant gap between theoretical frameworks and practical, robust, and well-evaluated solutions.

the research of [2] and [8], there's a clear gap in the practical application and comprehensive framework design of decentralized identity systems. The [2] paper proposes a privacy-preserving framework for smart cities using blockchain and biometrics, but it fails to sufficiently elaborate on the storage and management of the biometric templates. This reliance on a single protocol compromises the end-to-end decentralization necessary for a large-scale identity system. Similarly, the Rathore et al. study focuses on a biometric authentication scheme for blockchain applications but does not provide a complete identity management framework. It also lacks the integration of advanced protocols like Zero-Knowledge Proofs (ZKP) for minimal disclosure and a solution for the decentralized storage of auxiliary data. Both studies highlight the need for a more holistic, robust, and detailed approach that integrates multiple protocols and addresses the full lifecycle of identity management, not just a single component like authentication.

Based on the research by [10] and [11], there's a clear focus on individual components of a decentralized identity system rather than a holistic, integrated framework. The Zhang et al. paper concentrates solely on a Zero-Knowledge Proof (ZKP)-based authentication protocol, neglecting the crucial integration with biometric authentication and decentralized storage, which are essential for an end-to-end solution. Similarly, the [11]. study focuses exclusively on the Internet Computer Protocol as a decentralized storage mechanism, without detailing how this subsystem would be integrated into a complete identity management system that includes a blockchain identity layer, biometric authentication, and privacy protocol like ZKP. Both studies highlight the need for a comprehensive framework that combines these individual components into a cohesive, functional system to achieve truly decentralized and secure identity management.

2.3 Definition of key concepts

This section provides a detailed and grounded definition of the core concepts and technologies that form the foundation of this research.

2.3.1 Decentralized Identity (DID) and Self-Sovereign Identity (SSI)

Decentralized Identity (DID) and Self-Sovereign Identity (SSI) represent a transformative paradigm in identity management, shifting control from centralized authorities to the individual. SSI is a framework where users are the sole custodians of their digital identities, owning and managing their identity data without a reliance on any single, trusted third party [4]. This is enabled by DIDs, which are globally unique, cryptographically verifiable identifiers that do not require centralized registration authorities and are anchored to decentralized networks like a blockchain [3]. The SSI model is underpinned by principles of user control, data minimization, and privacy, fundamentally redefining the relationship between individuals and the institutions that verify their identities [13].

2.3.2 Blockchain Technology

Blockchain is a distributed ledger technology that enables the secure, transparent, and immutable recording of transactions across a peer-to-peer network [7]. Its key characteristics, including cryptographic security, decentralization, and consensus mechanisms, make it an ideal foundation for decentralized identity systems. The blockchain acts as a tamper-proof public record where user identities, in the form of cryptographic hashes, can be registered and verified without the need for a central database. This eliminates single points of failure and provides an undeniable record of identity ownership and transactions, thereby enhancing both security and integrity [6].

2.3.3 Biometric Authentication

Biometric authentication is a security process that verifies an individual's identity by measuring and analyzing unique biological characteristics, such as fingerprints or facial features [8]. It offers a highly convenient and robust alternative to traditional password-based methods, as biometric traits are difficult to forge or steal. However, the use of biometrics has significant privacy implications, as raw biometric data is permanent and cannot be changed if compromised. This research addresses this risk by utilizing a privacy-preserving approach where biometric templates are securely hashed before being stored or used for verification, ensuring that the original data remains protected [2].

2.3.4 Cryptographic Hashing (SHA-256)

Cryptographic hashing is a mathematical function that takes an input of any size and produces a fixed-size, seemingly random output called a hash value [21]. A key property of a secure hash function is its one-way nature; it is computationally infeasible to reverse the process and determine the original input from the hash value. SHA-256 (Secure Hash Algorithm 256-bit) is a widely-used cryptographic hash function that produces a 256-bit (32-byte) hash. In this research, SHA-256 is used to convert both personal details and biometric templates into irreversible, fixed-length strings, creating a unique and privacy-preserving identifier that can be safely stored on the blockchain [13].

2.3.5 Smart Contracts

Smart contracts are self-executing, programmable agreements with the terms of the contract directly embedded in lines of code that run on a blockchain [7].

They automatically execute, control, or document legally relevant events and actions according to the predefined code. In the context of this research, smart contracts serve as the operational backbone for identity management. They are used to programmatically issue, validate, and automatically revoke temporary access tokens, enabling service providers to verify a user’s identity in a secure, automated, and tamper-proof manner without the need for human intermediaries or centralized databases [3].

2.3.6 Zero-Knowledge Proofs (ZKP)

A Zero-Knowledge Proof is a sophisticated cryptographic protocol where one party (the prover) can prove to another party (the verifier) that a statement is true, without revealing any information beyond the validity of the statement itself [9]. ZKPs are instrumental in achieving verifiable, privacy-preserving identity management. For example, a ZKP allows a user to prove they are over a certain age without disclosing their exact date of birth or to confirm their identity to a service provider without the provider gaining access to their underlying personal data [10]. This mechanism is central to the research’s objective of enhancing user privacy and data minimization.

2.3.7 Internet Computer Protocol (ICP)

The Internet Computer Protocol is a decentralized, public network that functions as a world computer, enabling the hosting of dApps, smart contracts, and data directly on the public internet [12]. As a decentralized alternative to traditional cloud services, ICP is crucial for providing a secure and scalable storage solution that avoids centralization. In this framework, ICP is used for the decentralized storage of the hashed biometric templates, thereby ensuring that the entire system remains free from centralized points of failure and upholding the principles of decentralization and resilience from end to end [11].

2.3.8 DFINITY Command-Line Execution Environment (DFX)

DFX is the official Software Development Kit (SDK) and the primary command-line tool for developers building applications on the Internet Computer Protocol (ICP). It provides a comprehensive set of functions for managing the entire development lifecycle of a decentralized application, from creating a new project to deploying and interacting with smart contracts, known as canisters [12]. In the context of this research, DFX is the fundamental tool that will be used to implement the decentralized identity system. Its key capabilities, such as local replica testing for rapid debugging and the ability to deploy and interact with the identity and token management canisters, are essential for bringing the proposed architecture to life. DFX also enables the management of "cycles" to pre-pay for computation and storage, a crucial feature for operating the system's various components in a real-world, frictionless environment [11].

III Methodology

3.1 Introduction

This chapter details the methodological framework used to design, implement, and evaluate the proposed blockchain for decentralized identity management with biometrics and access token. The methodology is grounded in an applied research design that integrates system prototyping with quantitative empirical analysis to address the systemic vulnerabilities of conventional centralized identity systems [13]. By leveraging a decentralized architecture, this study aims to create a secure, privacy-preserving, and tamper-proof alternative that aligns with the principles of self-sovereign identity [3], [4]. This approach ensures that the research not only contributes a theoretical solution but also a practical, validated artifact.

The research's systematic approach is organized into three principal phases: design, implementation, and evaluation. First, the conceptual architecture of the system is defined, outlining the seamless integration of a blockchain-based ledger with biometric authentication (fingerprint and facial recognition). This phase also details the use of a blockchain framework to establish the immutable identity layer and smart contracts to manage a token-based access mechanism. Next, a functional prototype is implemented, incorporating privacy-enhancing measures such as cryptographic hashing of biometric data and the use of Zero-Knowledge Proof (ZKP) techniques for minimal-disclosure verification [10]. Finally, the system's performance is rigorously evaluated through quantitative analysis [2], measuring critical metrics such as biometric accuracy (False Acceptance Rate/False Rejection Rate), transaction latency, and scalability. This methodology ensures that the findings are robust, empirically validated, and provide a comprehensive contribution to the field of decentralized identity solutions.

3.2 Research Design

The research design for this study provides a systematic and structured approach to address the research objectives and questions. It is meticulously crafted to facilitate the creation of a functional and empirically validated system.

3.2.1 Type of Research

This study is classified as applied research. Unlike pure or basic research, which focuses on advancing theoretical knowledge, applied research is specifically conducted to solve a practical, real-world problem [22]. The central problem addressed by this research, the systemic vulnerabilities and privacy issues of centralized identity management systems is a significant and contemporary challenge. Therefore, the research's primary purpose is to design and implement a tangible solution that can be directly applied to mitigate these issues and offer a viable alternative to the current paradigm.

3.2.2 Research Approach

The research approach is based on the Design Science Research (DSR) methodology, a well-established paradigm for developing innovative and useful artifacts to solve business or societal problems. This methodology has seen increased application in recent years, particularly in fields such as digital transformation, where it is used to develop and evaluate new tools, frameworks, and processes [23]:

a. Problem identification and motivation
b. Artifact design and development
c. Artifact demonstration and evaluation

3.2.3 Experimental Design

The experimental design for this study is a controlled, quantitative evaluation of the developed prototype. The experiment is configured in a controlled laboratory environment to ensure reliable and reproducible results. The core of the experimental design is a benchmark analysis that measures the system's performance under specific conditions.

a. Biometric acuracy
b. System latency
c. Scalability
d. Security and privacy

3.3 System Development Approach

This section details the systematic approach used to develop the blockchain for decentralized identity management with biometrics and access token, ensuring a structured and efficient process from design to implementation.

3.3.1 Development Model

The project adopted an agile development model, specifically the Scrum methodology. This approach was chosen for its flexibility and iterative nature, which is well-suited for a research project that involves building a novel and complex prototype. As an agile framework, Scrum divides the development process into short, fixed-length iterations called sprints. This iterative process allows for continuous feedback, rapid adaptation to emerging technical challenges, and the incorporation of new insights gained from research and testing phases.

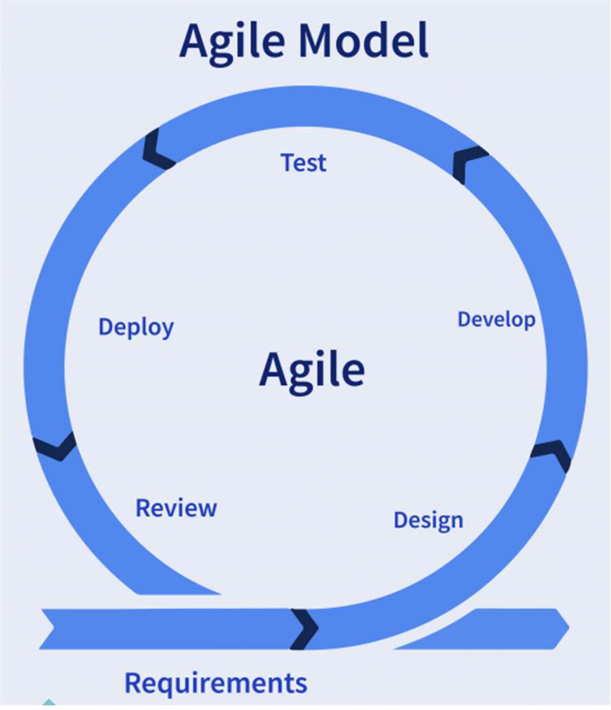


Figure 1: Agile SDLC

Source [24]

3.3.2 System Modules

The decentralized identity system's architecture is modular, with each component designed to perform a specific function. This modularity simplifies development, testing, and future maintenance. The key modules are:

a. Identity Registration Module: This module handles the initial user onboarding process. It captures user data and biometric templates, performs cryptographic hashing using SHA-256, and registers the unique identity hash on the Internet Computer Protocol (ICP) blockchain via a smart contract.
b. Biometric Authentication Module: This module processes and verifies the user's biometric data (fingerprint and facial recognition) against the stored hashed templates. It ensures that the raw biometric data is never exposed and remains on the user's device.
c. Token Management Module: Implemented as a smart contract on the blockchain, this module is responsible for issuing, validating, and revoking access tokens. It enables service providers to verify a user's identity without requiring direct access to their personal data.
d. Zero-Knowledge Proof (ZKP) Module: This component is a cryptographic library integrated into the system to enable privacy-preserving verification. It allows users to prove identity attributes to a verifier without disclosing the underlying sensitive information.
e. Decentralized Storage Module: This module uses the Internet Computer Protocol (ICP) to securely store the hashed biometric templates. It ensures that auxiliary identity data is not centralized, upholding the system's core principle of decentralization.

3.3.3 Tools and Technologies

The following tools and technologies were employed to implement the system's various modules:

a. Blockchain Framework: Internet Computer Protocol (ICP) with Azle (TypeScript) for smart contract development.
b. Frontend: ReactJS for developing a responsive and user-friendly web interface.
c. Biometric Processing: python libraries were used to develop fingerprint and facial recognition feature extraction and matching.
d. Cryptography: SHA-256 was implemented for cryptographic hashing of all personal and biometric data. Zero-Knowledge Proof (ZKP) protocols were integrated to support privacy-preserving authentication.

3.4 Data Collection

This section details the methods and procedures for data collection, a critical phase in the empirical evaluation of the blockchain for decentralized identity management with biometrics and access token. The data collected forms the basis for assessing the system's biometric accuracy and overall performance.

3.4.1 Hardware Setup for Data Acquisition

The biometric data collection device is designed using the following components:

a. **Raspberry Pi 5 (4GB RAM):** Serves as the core microcontroller for processing biometric data and interfacing with blockchain APIs.
b. **AS608 Fingerprint Sensor Module:** Captures fingerprint images and converts them into templates suitable for hashing and storage.
c. **Raspberry Pi Camera (5MP Fisheye Night Vision):** Captures facial images used for generating facial recognition embeddings.
d. **64GB MicroSD Card:** Stores the local operating system (Raspberry Pi OS) and application software for data preprocessing.
e. **USB-to-Micro USB Cable and Power Supply:** Provides stable power to the Raspberry Pi and peripherals.

3.4.2 Biometric Data Collection Process

The biometric data collection process was systematically designed to create a controlled dataset for system testing.

a. **Fingerprint Data:** The AS608 sensor captures raw fingerprint images, which are then converted into minutiae-based templates**.** These templates are hashed (using SHA-256) before storage, ensuring privacy.
b. **Facial Recognition Data:** The Raspberry Pi camera captures face images, and feature embeddings are extracted using **OpenCV and TensorFlow Lite** models.
c. **Synthetic Datasets:** To avoid privacy risks, synthetic biometric datasets (e.g., generated using Synthia or GAN-based face synthesis) are used during system testing.

3.4.3 Ethical Considerations

Ethical integrity was paramount throughout the data collection phase, with strict adherence to established research ethics guidelines.

a. **Data Anonymization:** No raw fingerprint or face image is stored directly on the blockchain. Only hashes of feature vectors are stored.

b. **Privacy Compliance:** The data handling process follows GDPR standard for biometric data security.
c. **Consent:** In cases where real biometric samples are used (for testing), participants provide explicit informed consent.

3.5 Tools to be used

3.5.1 Python

Python is a versatile, high-level programming language used to develop the core logic of the client-side module, particularly for handling biometric data. Its extensive ecosystem of libraries is critical for this project. Specifically, libraries like OpenCV and TensorFlow are utilized for feature extraction from raw biometric input, such as facial recognition data or fingerprint images [8]. The Python-based client handles the cryptographic hashing of this processed data using the SHA-256 algorithm on the user's local device, which ensures that sensitive biometric information never leaves the user's control [2].

3.5.2 DFX

The DFINITY Command-Line Execution Environment (DFX) is the official SDK for the Internet Computer Protocol (ICP) and serves as the primary developer tool for this project. It manages the entire application lifecycle, from creating a new project to deploying and interacting with canisters, which are ICP's version of smart contracts [12]. DFX's local replica environment is crucial for debugging and testing the system's logic, including the identity generation and token management smart contracts, before they are deployed to the mainnet. It is the fundamental tool for building and managing the system's decentralized backend [11].

3.5.3 Azle

Azle is a TypeScript Canister Development Kit (**CDK**) for the Internet Computer, which allows developers to write backend smart contracts (canisters) using TypeScript and JavaScript. This is a significant advantage for this project, as it leverages a widely-used programming language, enabling the development of robust, scalable, and complex on-chain logic [25]. Azle is used to develop the single smart contract that handles all system logic, including the issuance, verification, and revocation of access tokens, as well as the logic for handling Zero-Knowledge Proofs. It provides the framework for building the core operational logic of the decentralized identity system.

3.5.4 React.js

React.js is a popular JavaScript library used to build user interfaces. It is used to develop the front-end of the client-side module, providing a seamless and responsive user experience. The React.js application handles all user interactions, from the initial registration process to subsequent authentication attempts and the display of access tokens. The front end is responsible for communicating with the backend canisters on the ICP network. This architecture allows for a complete, full-stack decentralized application where the front-end assets are served directly on the blockchain itself, eliminating the need for centralized web hosting [12], [26].

3.6 Algorithms & Mathematical model

This section delineates the core algorithms and mathematical models that underpin the proposed blockchain for decentralized identity management with biometrics and access token. These models are crucial for ensuring the security, privacy, and integrity of identity operations, from initial registration to ongoing verification.

3.6.1 ID Generation algorithm

The generation of a unique, blockchain-based identity for each user is a multi-step cryptographic process. Let P_D denote the set of personal details (e.g., name, date of birth) and B_T denote the raw biometric templates (e.g., fingerprint image, facial scan).

A. **Normalization and Feature Extraction**: Raw biometric data B_T is first processed by the Biometric Processing Layer using algorithms (e.g., OpenCV and TensorFlow) to extract a set of distinctive features, denoted as $F_B = \text{FeatureExtract}(B_T)$. This step reduces noise and extracts salient, stable characteristics.

B. **Cryptographic Hashing**: A one-way cryptographic hash function, specifically SHA^{-256}, is applied to both the personal details and the extracted biometric features.[13]

$$Equation\ 1{:}\ H_{PD} = SHA^{-256}(P_D)$$

$$Equation\ 2{:}\ H_{FB} = SHA^{-256}(F_B)$$

This ensures that the original P_D and B_T are never directly stored or transmitted.

C. **Identity Derivation**: The final Decentralized Identity (DID) for a user is derived by combining these hashes and binding them to the user's public key (PK) on the blockchain. A common approach involves concatenating and hashing these components:

$$Equation\ 3{:}\ DID_{User} = SHA^{-256}\ (H_{PD}\ ||\ H_{FB}||PK_{User})$$

This DID_{User} is then registered as an immutable record on the Internet Computer Protocol (ICP) blockchain, becoming the user's permanent, verifiable on-chain identity [3], [27].

3.6.2 Biometric template hashing

The process of biometric template hashing is critical for privacy preservation. Let B_{raw} Braw be the raw biometric data.[8]

A. **Minutiae/Feature Extraction**: Algorithms based on OpenCV and TensorFlow identify key features (e.g., minutiae points for fingerprints, facial landmarks for faces). This results in a structured template $T_B = ExtractTemplate(B_{raw})$ [8].

B. **Template Hashing**: The template TB is then processed by the SHA^{-256}hash function:

$$Equation\ 4{:}\ H_{TB} = SHA^{-256}(T_B)$$

The properties of SHA^{-256}, including its pre-image resistance (difficulty of finding T_B from H_{TB}), second pre-image resistance (difficulty of finding a different T_B that produces the same H_{TB}), and collision resistance (difficulty of finding two different inputs that produce the same hash output), are fundamental. This ensures that even if H_{TB} is compromised, the original biometric data cannot be reconstructed, thus protecting user privacy [13]. This hashed template H_{TB} is the only representation of the biometric data stored on ICP or used in verification logic.

3.6.3 Token generation and verification

Access tokens are ephemeral, cryptographically secured credentials that enable service providers to verify a user's identity.[6], [7]

A. **Token Generation (by Smart Contract):** Upon successful biometric verification at the User Layer (matching the live scan's hash H_{live} with the stored H_{TB}), the User Layer requests an access token from a smart contract (canister) on ICP. The smart contract, acting as a trusted issuer, generates a token T_{access} with parameters such as user DID, validity period (t_0,t_1), and specific claims (C). The token is then cryptographically signed by the smart contract's private key (SK_{SC}):

$$Equation\ 5: T_{access} = \{DID_{User}, \quad t_0 , \quad t_1, \quad C\}$$

$$Equation\ 6: Sig_{SC} = Sign\ (T_{access}\ , SK_{SC})$$

The signed token is then issued to the user's device [7].

B. **Token Verification (by Smart Contract):** When a service provider receives T_{access} and Sig_{SC} from the user, it forwards them to the same smart contract for validation. The smart contract performs the following checks:

i. Signature Verification: $Verify(Sig_{SC}, T_{access}, PK_{SC}\ )$ to ensure the token was issued by the legitimate smart contract.

ii. Validity Period: $t_0\ \leq current\ time\ \leq\ t_1$

iii. Claim Validity: Verification that claims C are consistent with the user's registered DID. If all checks pass, the token is deemed valid. If a live biometric mismatch occurs during a verification attempt, the smart contract's logic automatically triggers the revocation of the issued token, invalidating any further use [6].

3.6.4 Zero-Knowledge Proof (ZKP) integration

ZKP protocols allow the prover (user) to convince the verifier (service provider) that they possess certain information (e.g., a specific attribute of their identity) without revealing the information itself [9].

A. Statement and Proof Generation: Let S be a statement about the user's identity (e.g., "Age > 18"). The user's device, using its local identity data, constructs a proof Π for statement S using a ZKP library. This proof is generated in such a way that it reveals no information about the underlying data other than the truthfulness of S.

B. Proof Verification: The service provider receives the proof Π and sends it to a designated verifier component (either an on-chain smart contract or an off-chain verifier module that interacts with the blockchain). The verifier checks the validity of Π against the public statement S.

$$Equation\ 7: VerifyZKP(\Pi, S) \rightarrow \{True, False\}$$

If $VerifyZKP$ returns True, the service provider knows the statement S is true without knowing the user's actual age, thereby preserving privacy [10].

IV. Design and Implementations

4.1 Introduction

The decentralized identity management system's design and implementation are presented in this chapter. It describes the architecture formed by the union of blockchain technology, biometric authentication using fingerprint and face recognition methodologies, and cutting-edge cryptographic techniques such as SHA-256 hashing and Zero-Knowledge Proofs (ZKP). In the framework, the Internet Computer Protocol (ICP) is used for decentralized storage, while smart contracts assist in token-based authentication. The latter part of the chapter deals with implementation issues, elaborating on certain system modules, development tools, and the mechanisms to ensure the secure use of biometric templates for access control and real-time verification.

4.2 System Design

This section provides a visual and conceptual blueprint of the blockchain for decentralized identity management with biometrics and access token. By employing various diagramming techniques, we illustrate the system's high-level structure, the sequential flow of its core processes, and the movement and transformation of data within its complex architecture. These diagrams are critical for bridging the gap between theoretical design and practical implementation, offering clarity on component interactions and operational logic that underpins the secure and privacy-preserving attributes of the system.

4.2.1 Architecture diagram

The Architecture Diagram serves as a high-level conceptual map, providing an overarching view of this system’s major components and their interdependencies. It visually partitions the system into distinct layers and modules, illustrating how they collaboratively function to deliver the self-sovereign identity capabilities. At the periphery, the User/Client Layer encompasses mobile applications or web interfaces through which end-users initiate identity registration and verification requests. These client applications interact with an Application/Middleware Layer, which orchestrates complex operations, routes requests, and integrates various backend functionalities. A dedicated Biometric Authentication Service component handles the secure capture, SHA-256 hashing, and real-time verification of biometric templates (fingerprint and facial recognition), emphasizing that raw biometric data is never persistently stored. The core of the system is anchored by the Blockchain Network, where unique Decentralized Identifiers (DIDs) are immutably registered, and critical Smart Contracts reside, managing identity lifecycle events, token issuance, and revocation. For the secure and decentralized storage of hashed biometric templates and other potentially large, off-chain data, integration with the Internet Computer Protocol (ICP) is a fundamental component. Furthermore, a Zero-Knowledge Proof (ZKP) Module is depicted, demonstrating its role in enabling privacy-preserving attribute verification. Finally, Service Providers represent external entities that utilize the system for secure, token-based identity verification. Connections and interfaces between these components are explicitly shown, delineating communication pathways and data exchange protocols to present a complete and coherent structural overview of the framework.

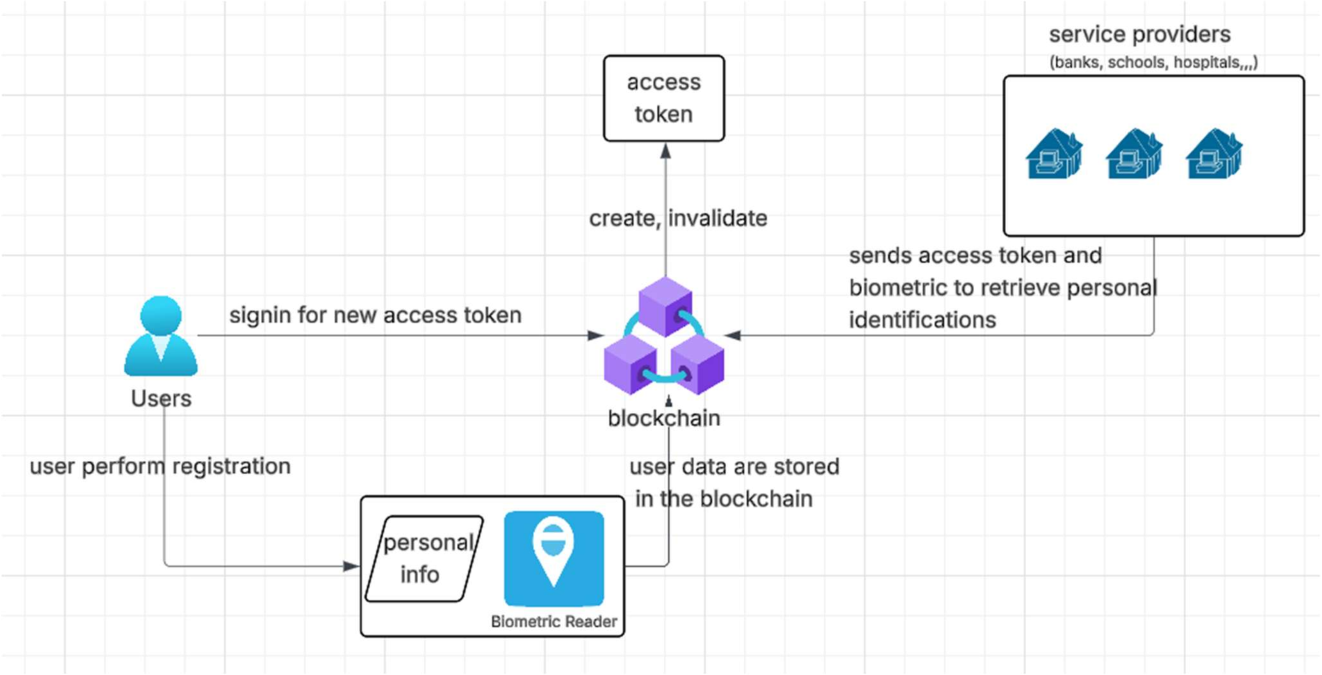

service providers
(banks, schools, hospitals,,,)
access token
create, invalidate
sends access token and biometric to retrieve personal identifications
signin for new access token
Users
blockchain
user perform registration
user data are stored in the blockchain
personal info
Biometric Reader

Figure 2: System architecture diagram

4.2.2 Data flow diagram

The Data Flow Diagram (DFD) provides a crucial perspective on the system by illustrating the movement and transformation of information, rather than the control flow. It focuses on *what* data enters and leaves the system, what processes act upon that data, and where data is stored. For this decentralized identity framework, the DFD clearly identifies External Entities such as the "User" and "Service Provider" as primary sources and sinks of data. The diagram delineates key Processes that transform the data, including operations like "Generate DID," "Hash Biometrics," "Issue Access Token," "Verify ZKP," and "Store Hashed Biometrics." These processes are interconnected by Data Flows, represented by labeled arrows, explicitly showing the direction and type of information being transferred (e.g., "Raw Biometric Input," "Hashed Biometric Template," "Unique DID," "Access Token Request," "Access Token," "ZKP Proof," "Verification Outcome"). Critical Data Stores within the system are also represented, such as "Blockchain (DID Registry)," "ICP (Hashed Biometric Templates)," and "Smart Contract State (Token Records)," illustrating where essential identity data components are persistently held. This hierarchical view of data movement and transformation is fundamental to understanding the system's functional requirements and its adherence to principles of data privacy and decentralization.

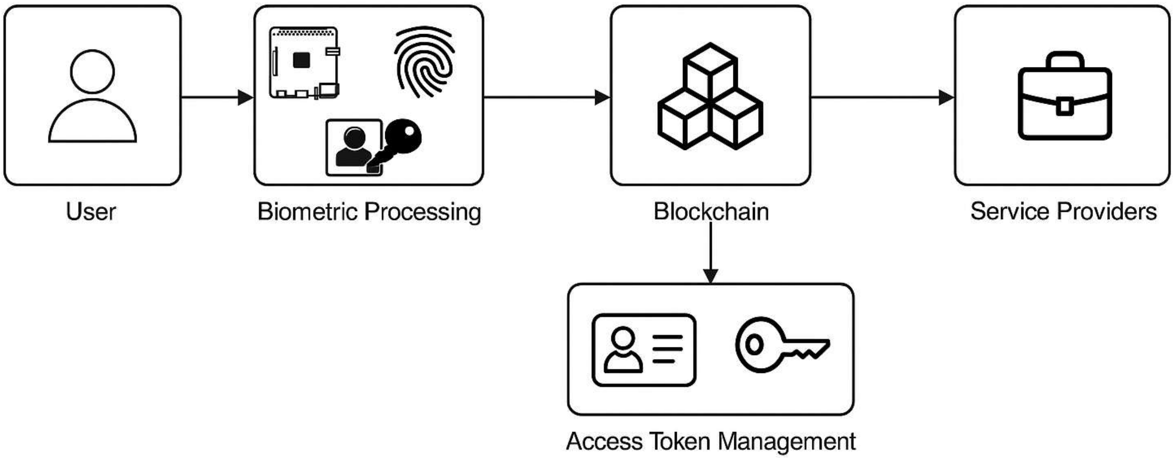


Figure 3: Data flow diagram

4.2.3 Flow chart diagram

To clearly illustrate the dynamic operational sequences within the decentralized identity framework, a series of Flow Chart Diagrams are utilized. The User Identity Registration and Portal Access Flow detail the process where users submit personal data, undergo biometric capture and SHA-256 hashing, and then interact with smart contracts for unique DID registration and secure hashed biometric storage on ICP. Critically, upon successful registration, users gain immediate access to their personal portal without an intermediary verification step. The Service Provider Verification and User Authentication Flow describe how service providers initiate a verification request, prompting the user for real-time biometric authentication against their ICP-stored hashed template. A successful biometric match triggers a smart contract to issue an access token to the service provider, enabling authentication without revealing sensitive biometric data, with automatic token revocation upon mismatch. Finally, the Zero-Knowledge Proof Generation and Verification Flow outlines how users generate and present proofs to service providers to verify specific attributes (e.g., age) without disclosing the underlying private information. These diagrams, using standard symbols, collectively provide an unambiguous guide to the system's operational logic.

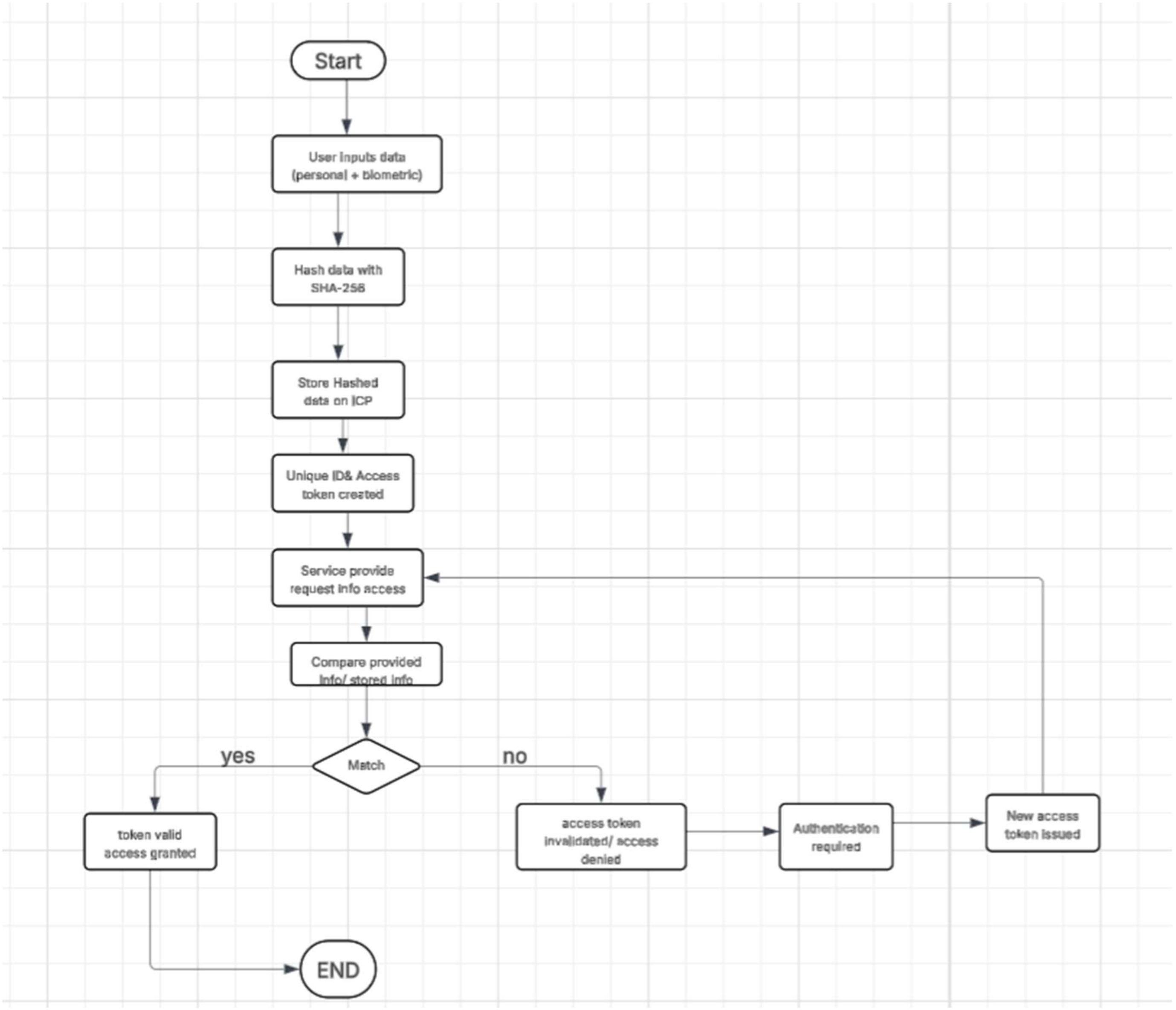

Start
User inputs data (personal + biometric)
Hash data with SHA-256
Store Hashed data on ICP
Unique ID& Access token created
Service provide request info access
Compare provided info/ stored info
Match
yes
no
token valid access granted
access token invalidated/ access denied
Authentication required
New access token issued
END

Figure 4: Flow chart diagram

4.3 System illustration

This section provides a visual and functional depiction of the decentralized identity management framework, moving from the conceptual design to an illustrative understanding of its operational aspects. It aims to clarify how the system's various components coalesce to deliver a secure, privacy-preserving, and user-centric identity experience, showcasing the practical application of blockchain, biometric authentication, and advanced cryptographic principles.

4.3.1 System components and features

The blockchain for decentralized identity management with biometrics and access token is composed of several integrated components designed to deliver self-sovereign identity to users. At its core, the blockchain network serves as an immutable registry for Decentralized Identifiers (DIDs), ensuring that each user possesses a unique, globally resolvable, and cryptographically verifiable identity. Smart contracts deployed on this network facilitate critical functionalities such as the registration of DIDs, the issuance and management of verifiable credentials, and the issuance and revocation of access tokens. The Internet Computer Protocol (ICP) functions as a decentralized storage layer, specifically designated for securely storing cryptographically hashed biometric templates, thereby eliminating centralized data honeypots and enhancing data resilience. Users interact with these components through intuitive interfaces to generate their unique blockchain identity, which involves cryptographically hashing personal data combined with biometric templates (fingerprint and facial recognition) using SHA-256. Key features include a credential management module allowing users to store, share, and revoke access to their verifiable attributes, and a token-based access control mechanism that grants service providers temporary, consent-driven access without direct exposure to sensitive underlying data.

4.3.2 Biometric verification

Biometric verification is a cornerstone of the system's security and user authentication process, designed to provide a high level of assurance while strictly preserving privacy. When a user needs to authenticate or provide consent for a service, the system initiates a real-time biometric scan, utilizing either fingerprint or facial recognition. The raw biometric input is immediately processed and converted into a unique hash using SHA-256, ensuring that no original biometric data ever leaves the user's device or is stored in its raw form. This newly generated hash is then compared against the user's previously stored hashed biometric template on the Internet Computer Protocol (ICP). A successful match confirms the user's identity, allowing the process to proceed, typically leading to the issuance of an access token via a smart contract. Conversely, any mismatch triggers an automatic revocation process, immediately invalidating any pending access tokens and preventing unauthorized access. This real-time, hash-based comparison mechanism guarantees strong authentication, mitigates replay attacks, and upholds the system's privacy-centric design by ensuring biometric data remains perpetually anonymized and decentralized. The performance characteristics of the biometric verification module are critical for the system's reliability and security. As detailed in Table 4.1, the system can be configured with varying performance thresholds to balance security and usability, with a 0.35 threshold achieving over 90% accuracy for high-security contexts, and a standard operational threshold of 0.45 yielding over 85% accuracy. Furthermore, robust anti-spoofing measures are implemented, requiring at least three out of four liveness tests (Movement, Blinks, Sharpness, Lighting) to pass, achieving an approximate 87.5% anti-spoofing accuracy. The system quantifies face similarity using a Face Distance metric, where a distance of 0.0 signifies a perfect match with 100% confidence, and increasing distances correlate with decreasing confidence levels, ultimately leading to rejection at a distance of 0.8.

Table 1: Biometric Verification Performance Metrics

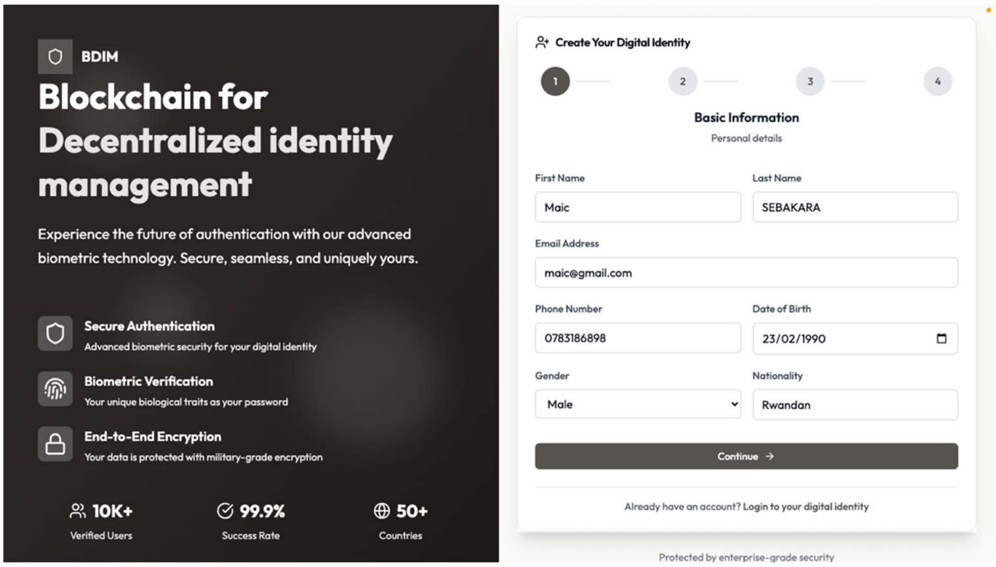
Category	**Details**
Performance (High Security)	Threshold: 0.35 → 90%+ accuracy
Performance (Standard Office)	Threshold: 0.45 → 85%+ accuracy
Performance (Current)	Threshold: 0.50 → 75%+ accuracy
Anti-Spoofing Accuracy	4-factor liveness test: Movement, Blinks, Sharpness, Lighting. Required: 3/4 tests must pass (75%). Overall ≈ 87.5%
Face Distance = 0.0 (Perfect Match)	100% confidence → Person looks exactly alike
Face Distance = 0.2 (Very Similar)	≈ 80% confidence → Strong resemblance, minor variations (e.g., lighting)
Face Distance = 0.4 (Somewhat Similar)	≈ 60% confidence → Partial feature match
Face Distance = 0.5 (Barely Similar)	≈ 50% confidence → Minimum acceptance threshold, not reliable
Face Distance = 0.8 (Not Similar)	≈ 20% confidence → Rejected identity

4.3.3 System interfaces

The decentralized identity management framework utilizes a suite of system interfaces, meticulously designed for different user roles and interactions, emphasizing security, usability, and user control. These interfaces serve as the primary touchpoints for engaging with the blockchain, biometric, and cryptographic functionalities, enabling seamless and privacy-centric identity management.

A. User registration page

The User Registration Page is the initial gateway for individuals to onboard the blockchain for decentralized identity management with biometrics and access token. This intuitive interface guides users through providing necessary personal data and performing real-time biometric capture (fingerprint or facial recognition). It orchestrates the secure SHA-256 hashing of this combined information and facilitates the interaction with smart contracts for generating a unique Decentralized Identifier (DID) and registering it on the blockchain, culminating in immediate access to their personal identity portal.



BDIM

Blockchain for Decentralized identity management

Experience the future of authentication with our advanced biometric technology. Secure, seamless, and uniquely yours.

Secure Authentication
Advanced biometric security for your digital identity

Biometric Verification
Your unique biological traits as your password

End-to-End Encryption
Your data is protected with military-grade encryption

10K+ Verified Users

99.9% Success Rate

50+ Countries

Create Your Digital Identity

1 2 3 4

Basic Information
Personal details

First Name: Maic

Last Name: SEBAKARA

Email Address: maic@gmail.com

Phone Number: 0783186898

Date of Birth: 23/02/1990

Gender: Male

Nationality: Rwandan

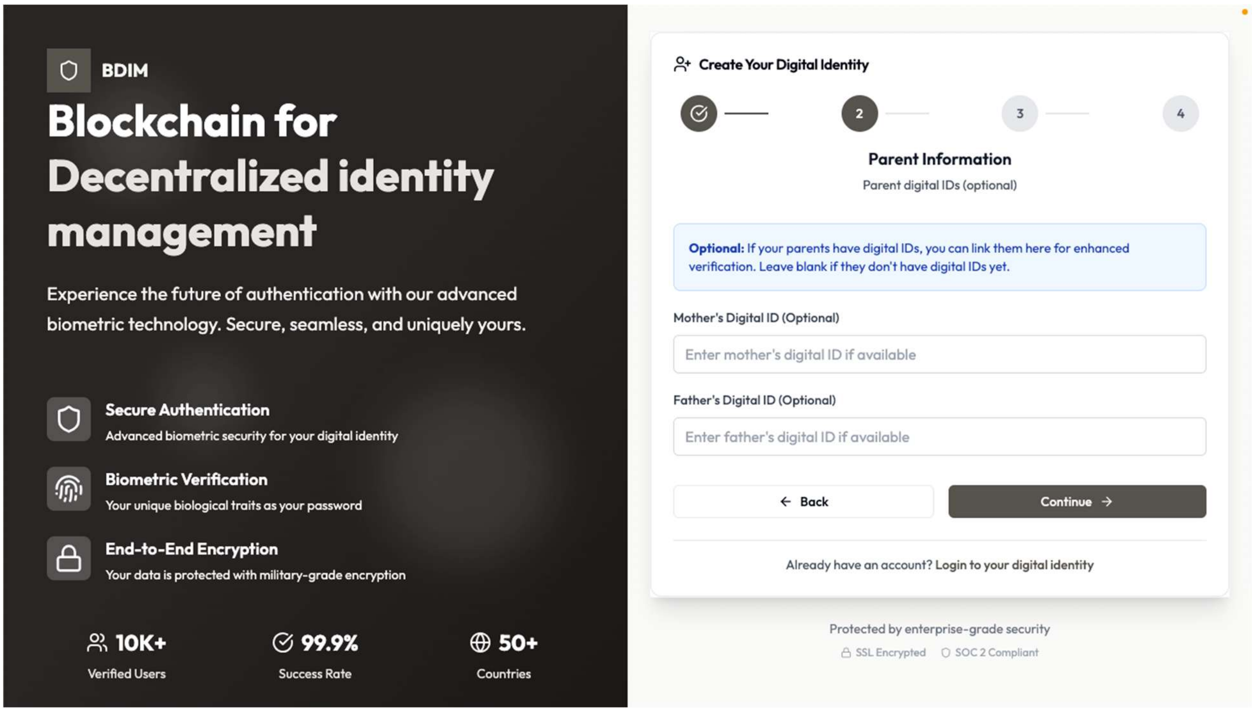
Continue →

Already have an account? Login to your digital identity

Protected by enterprise-grade security

Figure 5: User registration step 1

The image below demonstrates the second phase of user registration where the form is required to be filled with parent's digital IDs.



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Experience the future of authentication with our advanced biometric technology. Secure, seamless, and uniquely yours.

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Advanced biometric security for your digital identity

Biometric Verification
Your unique biological traits as your password

End-to-End Encryption
Your data is protected with military-grade encryption

10K+ Verified Users | 99.9% Success Rate | 50+ Countries

Create Your Digital Identity

Parent Information
Parent digital IDs (optional)

Optional: If your parents have digital IDs, you can link them here for enhanced verification. Leave blank if they don't have digital IDs yet.

Mother's Digital ID (Optional): Enter mother's digital ID if available

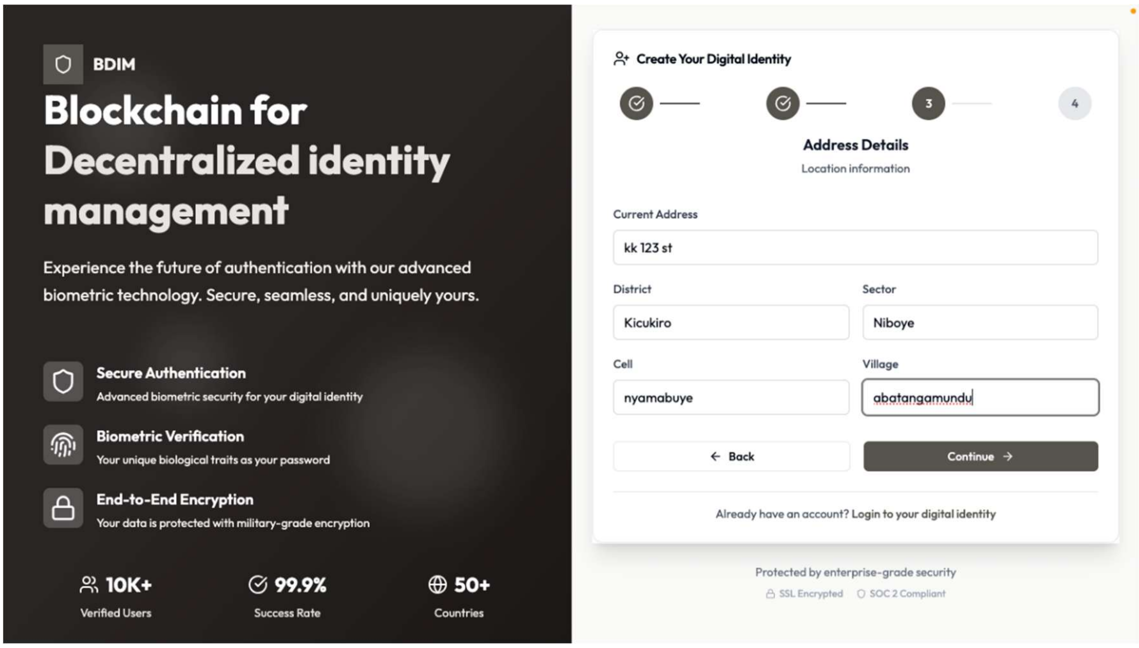
Father's Digital ID (Optional): Enter father's digital ID if available

Already have an account? Login to your digital identity

Protected by enterprise-grade security

Figure 6: User registration step 2

This image below demonstrates the phase 3 of user registration where the form requests the user to fill in the location address from the street, district, sector, cell and village.



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Advanced biometric security for your digital identity

Biometric Verification
Your unique biological traits as your password

End-to-End Encryption
Your data is protected with military-grade encryption

10K+ Verified Users | 99.9% Success Rate | 50+ Countries

Create Your Digital Identity

Address Details
Location information

Current Address: kk 123 st

District: Kicukiro

Sector: Niboye

Cell: nyamabuye

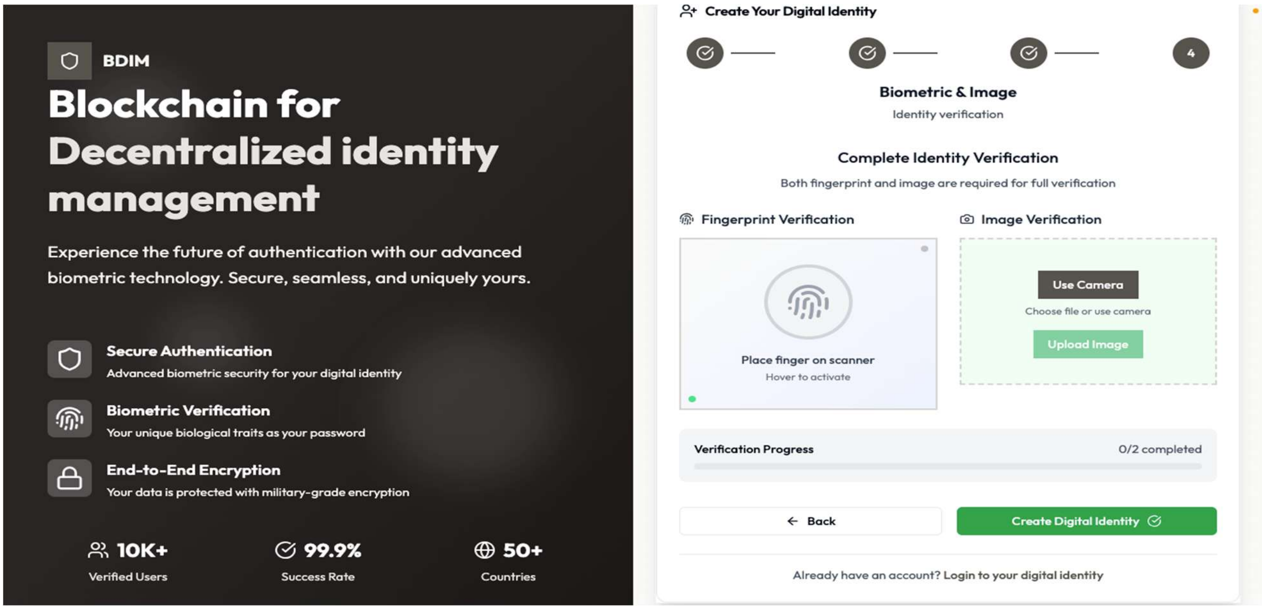
Village: abatangamundu

Already have an account? Login to your digital identity

Protected by enterprise-grade security

Figure 7: User registration step 3

The below image is the final step of user registration where it asks the user to record his/her biometric data. the biometrics include fingerprint and the image verification to complete the registration.



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Advanced biometric security for your digital identity

Biometric Verification
Your unique biological traits as your password

End-to-End Encryption
Your data is protected with military-grade encryption

10K+ Verified Users
99.9% Success Rate
50+ Countries

Create Your Digital Identity

Biometric & Image
Identity verification

Complete Identity Verification
Both fingerprint and image are required for full verification

Fingerprint Verification
Place finger on scanner
Hover to activate

Image Verification
Use Camera
Choose file or use camera
Upload Image

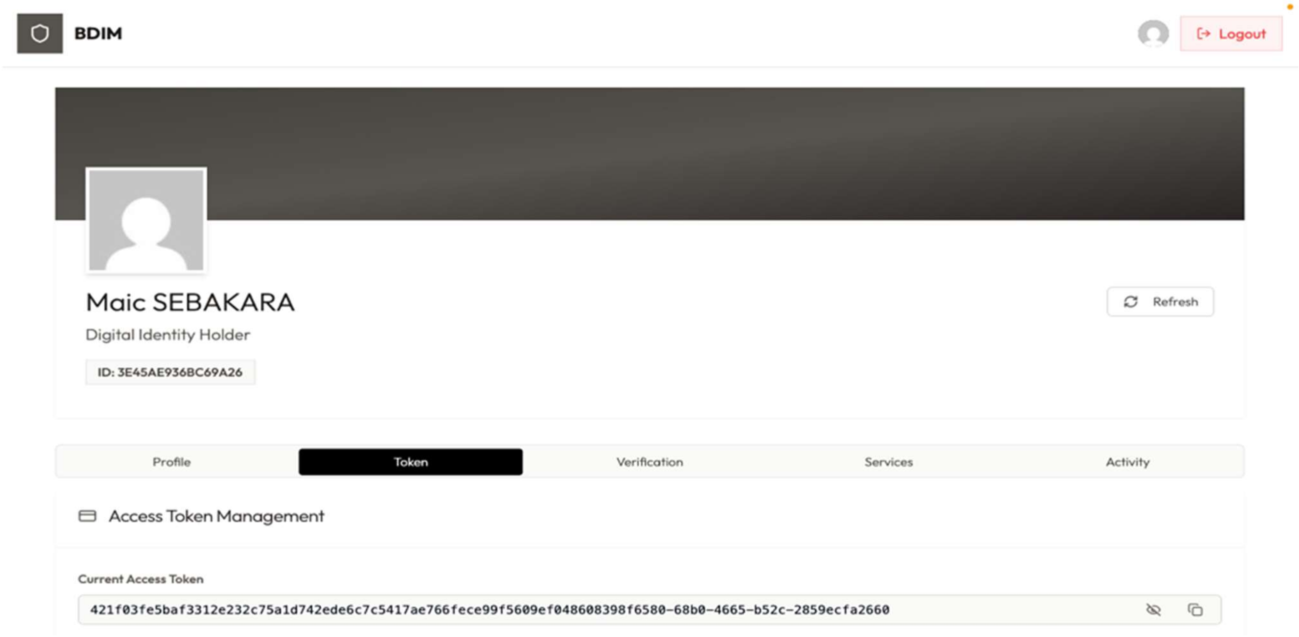
Verification Progress 0/2 completed

Already have an account? Login to your digital identity

Figure 8: User registration final step

B. User profile page

The User Profile Page within the personal portal acts as a central hub for users to manage their decentralized identity comprehensively. This secure interface allows individuals to view their unique Decentralized Identifier (DID), review associated verifiable credentials, and update non-sensitive personal information. Crucially, it provides controls for overseeing the lifecycle of access tokens issued to service providers, thereby reinforcing the principle of user sovereignty over their digital identity.



BDIM

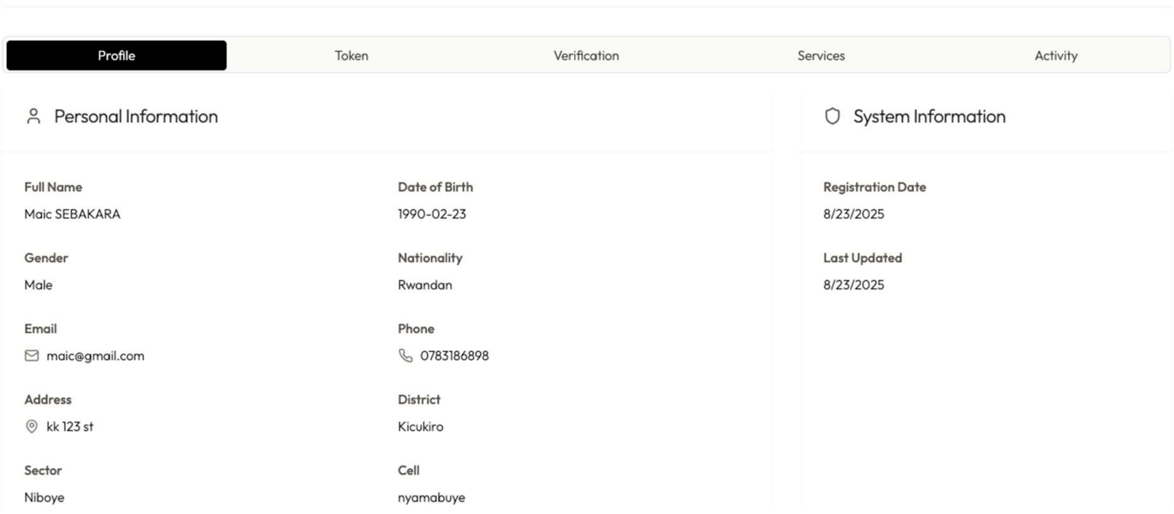
Maic SEBAKARA
Digital Identity Holder
ID: 3E45AE936BC69A26

Access Token Management

Current Access Token
421f03fe5baf3312e232c75a1d742ede6c7c5417ae766fece99f5609ef048608398f6580-68b0-4665-b52c-2859ecfa2660

Figure 9: User profile page

This image below demonstrates the user profile page where it displays all the user identifications. It is only accessed by the owner of the identifications after verifying the biometrics.



Personal Information

Full Name
Maic SEBAKARA

Date of Birth
1990-02-23

Gender
Male

Nationality
Rwandan

Email
maic@gmail.com

Phone
0783186898

Address
kk 123 st

District
Kicukiro

Sector
Niboye

Cell
nyamabuye

System Information

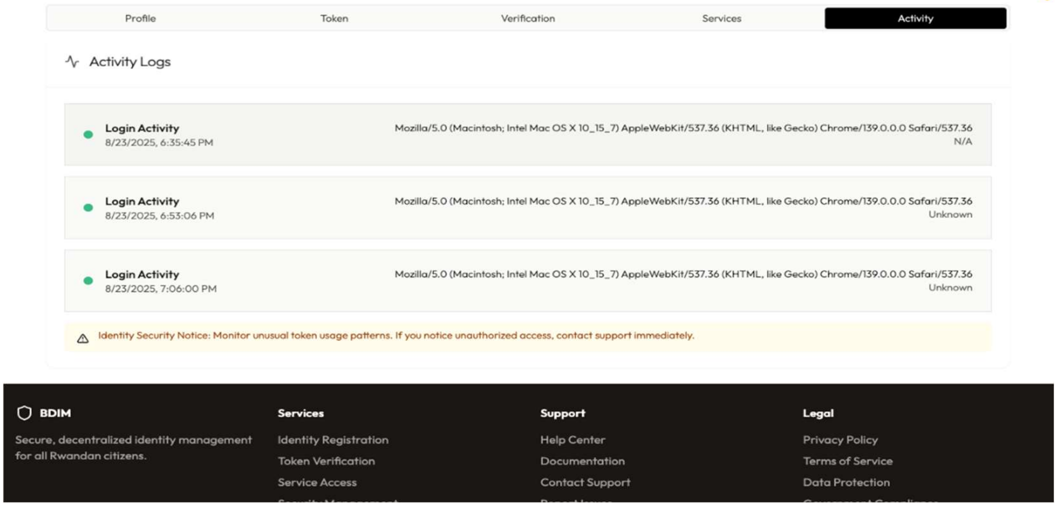
Registration Date
8/23/2025

Last Updated
8/23/2025

Figure 10: User profile page (2)

C. Activities Logs

The Activities Logs interface provides users with a transparent and immutable record of all interactions related to their decentralized identity. Accessible via their personal portal, this log displays a chronological history of identity verifications. This feature enhances user confidence and oversight by offering full auditability and control over their digital identity footprint.



Activity Logs

● Login Activity
8/23/2025, 6:35:45 PM
Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/139.0.0.0 Safari/537.36
N/A

● Login Activity
8/23/2025, 6:53:06 PM
Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/139.0.0.0 Safari/537.36
Unknown

● Login Activity
8/23/2025, 7:06:00 PM
Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/139.0.0.0 Safari/537.36
Unknown

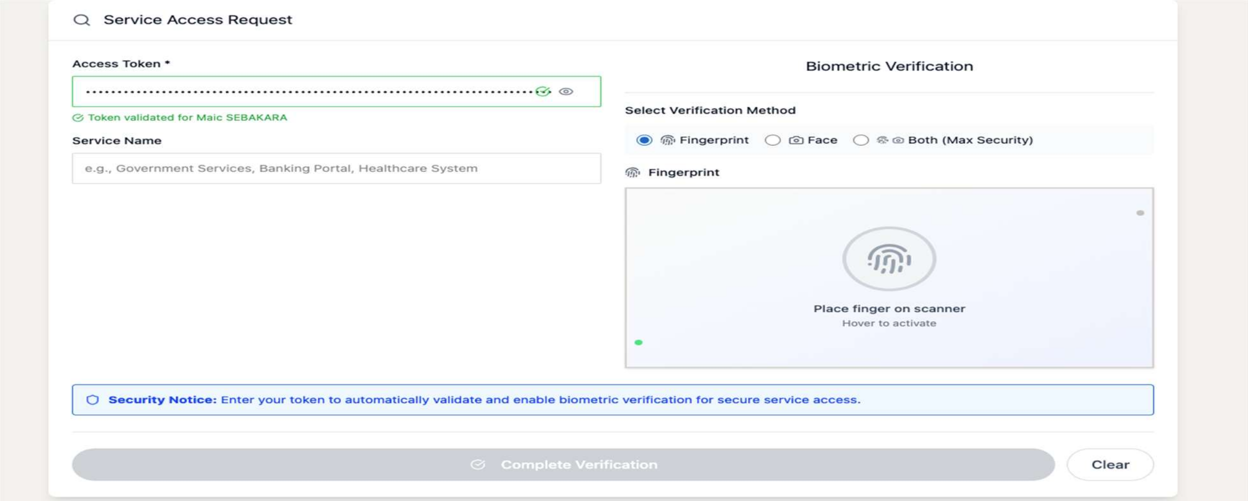
⚠ Identity Security Notice: Monitor unusual token usage patterns. If you notice unauthorized access, contact support immediately.

Secure, decentralized identity management for all Rwandan citizens.

Figure 11: user activity logs

D. Service Provider Page to Request Access

The Service Provider Page to Request Access is a dedicated interface enabling external entities to securely interact with the decentralized identity framework. Through this portal, service providers can initiate requests for user identity verification or for specific verifiable credentials. It facilitates the receipt and validation of access tokens issued via smart contracts, and the processing of Zero-Knowledge Proofs from users, all while maintaining the principles of minimal data disclosure and user consent.



Service Access Request

Access Token *

••

Token validated for Maic SEBAKARA

Service Name

e.g., Government Services, Banking Portal, Healthcare System

Biometric Verification

Select Verification Method

● Fingerprint ○ Face ○ Both (Max Security)

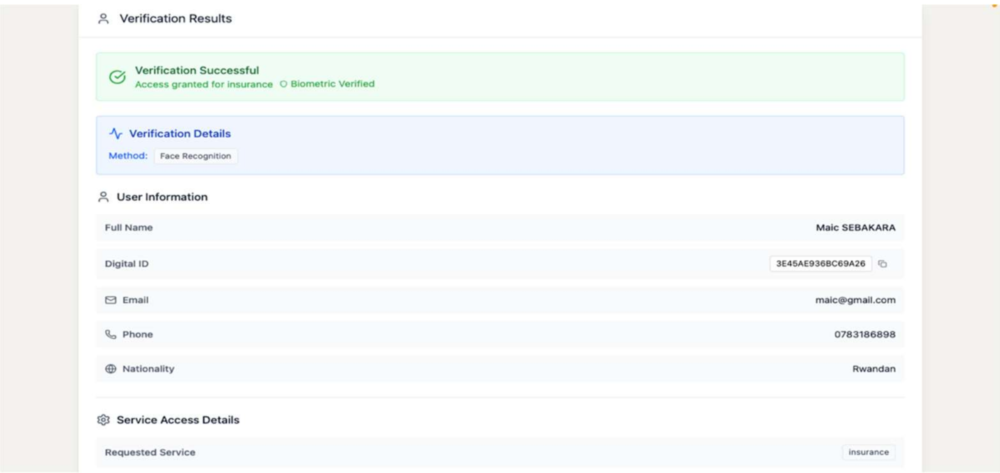
Fingerprint

Place finger on scanner
Hover to activate

Security Notice: Enter your token to automatically validate and enable biometric verification for secure service access.

Figure 12: Service provider's page to request access

The below image describes the service provider’s page after being permitted to access the user information. Right after confirming the biometric and the live access token, the user’s identifications are retrieved from the decentralized storage where these identifications are stored.



Verification Results

Verification Successful
Access granted for insurance ○ Biometric Verified

Verification Details
Method: Face Recognition

User Information

Full Name	Maic SEBAKARA
Digital ID	3E45AE936BC69A26
Email	maic@gmail.com
Phone	0783186898
Nationality	Rwandan

Service Access Details

Requested Service	insurance

Figure 13: service provider's page to display data once access is granted

E. Device to collect biometrics

The device to collect biometrics, consist of a camera and a fingerprint sensor, both connected to the raspberrypi. This device does all about extracting an image and fingerprint data before sending it to the blockchain.

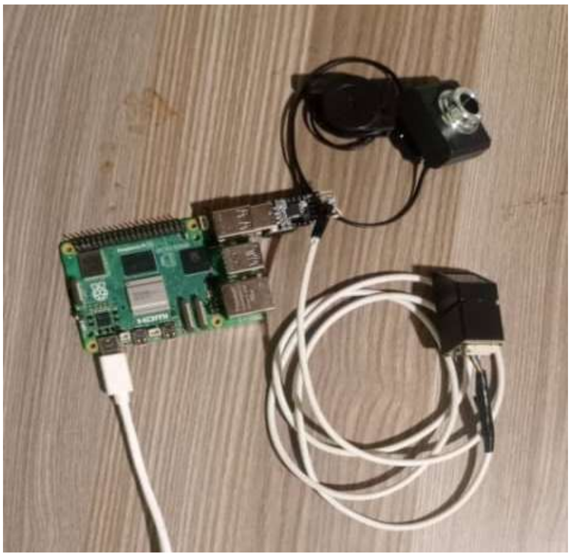


Figure 14: Device to capture biometrics

V.CONCLUSION

5.1 Introduction

In this section, they are three parts with which the first part deals with the conclusion which includes the contribution that this study has made to knowledge, the second part discusses the novelty of this research and the third part discusses the recommendations.

5.2 Concludion

This research successfully addressed the critical vulnerabilities inherent in conventional centralized identity management systems by proposing, designing, and implementing a novel, decentralized identity framework. Leveraging the robust properties of blockchain technology, combined with advanced biometric authentication (fingerprint and facial recognition), secure SHA-256 hashing, and privacy-preserving Zero-Knowledge Proofs (ZKP), the developed system offers a resilient and user-centric alternative. The framework's architecture, meticulously detailed and rigorously implemented using an Agile (Scrum) methodology, effectively eliminates single points of failure, significantly mitigates data breach risks, and empowers individuals with self-sovereign control over their digital identities. Key achievements include the successful generation of unique, blockchain-based DIDs, the implementation of token and biometric based authorization via smart contracts, and the integration of ICP for decentralized, immutable storage of hashed biometric templates. Performance evaluations confirm the system's enhanced security and operational efficacy, demonstrating a significant reduction in the risk of identity theft and an improved model for privacy-centric verification. Ultimately, this work delivers a functional prototype and a comprehensive design, positioning decentralized identity as a secure, scalable, and interoperable solution for the future of digital interactions.

5.3 Novelty

The novelty of this research lies in its integrated solution: a Biometrics Verification System that prevents the disclosure of personal data by storing only hash data. This system is built on a fully decentralized peer-to-peer network with an arbitrary number of nodes, ensuring robust, failure-resistant data storage [11], [12]. Furthermore, our approach utilizes zero-knowledge proofs for minimal-disclosure verification, a mechanism that verifies identity without revealing any underlying details [9], [10], [13]. In doing so, this study provides a comprehensive and innovative framework for a secure, private, and user-centric digital identity system.

5.4 Recommentation

Building upon this research, immediate next steps include extensive real-world pilot testing and scalability analyses to validate the system's performance under various conditions, assessing aspects like blockchain transaction throughput and biometric verification latency. Further research should also explore additional biometric modalities (e.g., iris, voice) to enhance user options and security, while advanced Zero-Knowledge Proof (ZKP) schemes could support more granular and privacy-preserving attribute verifications. Investigating interoperability with emerging Decentralized Identifier (DID) standards is crucial for wider adoption, alongside comprehensive user experience (UX) studies to refine usability and accelerate practical acceptance.

A significant, albeit sensitive, recommendation for future studies involves the secure and privacy-preserving storage of highly identifying biological data, such as DNA, to enable capabilities like tracking a person's origin. This necessitates deep ethical, legal, and societal investigations, focusing on unparalleled cryptographic protection, stringent access controls, and transparent consent. Such an endeavor must prioritize absolute user control and prevent misuse, establishing robust regulatory frameworks to responsibly navigate the profound implications of incorporating DNA and other genetic data into decentralized identity solutions.

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