A Trust-Aware Blockchain-XR Framework for Rehabilitation and Adaptive IoMT Systems

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Abstract

The Gait-Wheelchair is widely used as a rehabilitation navigation device in helping disabled people enhance their movement across surroundings; hence, many patients find it difficult to adapt to the cost and usability of such an invasive device. Diffenrent study as been conducted on how the integration of an Internet of Medical Things (IoMT) using immersive haptic systems as an approach to leverage the significant safety and cognitive challenges faced by wheelchair users when navigating recovery training, at present most of the research uses Electroencephalogram (EEG) or Brain-Computer-Interface (BCI)-based rehabilitation which is not adaptive due to it reliance on invasive Head-Mounted Devices (HMD) and signal reliance affective on the real-time adaptation and record track of user's cognitive performance. The proposed system integrates an immersive Extended Reality (XR) system, a hand-tracking-based locomotion system, intelligent traffic signals, a Non-Player Character (NPC), and cryptographic verification logging. In addition, our work implemented blockchain-enabled data privacy and tampering-based detection on a real-time IoMT framework for patient cognitive event records. Existing studies show that data privacy has been one of the key limitations in the proposed digital adaptive rehabilitation. This work implements a lightweight hashing method using SHA-256, unlike recent discoveries that rely on the wavelet transform watermark, which utilises invasive signal electrode output before post-data security is executed. The study shows that Internet of Medical Things (IoMT) data can be captured in real-time to improve cognitive assessment by integrating an XR-based autonomous-driven hand motor functionality control using META-XR, and that tamper-free patient data can be cryptographically secure in real-time execution without reliance on invasive signal equipment.

Keywords: IoMT, XR, Virtual Reality, Wheelchair Rehabilitation, Traffic Safety, Blockchain, SHA-256, Metaverse, Cognitive Assessment, NPC

1. Introduction

Immersive rehabilitation is one of the emerging Internet of Medical Things (IoMT) platforms to enhance healthcare; hence, ensuring integrity and authenticity goes a long way in maintaining the patient's cognitive data record. XR-based rehabilitation platforms mostly rely on a centralised data storage approach from real-time data accumulated during the motor functional activity and post-session patient data analysis [1]. This way, users' performance and records are vulnerable to tampering, and they can be easily manipulated. This work introduces Blockchain as a trust mechanism, specifically cryptographic hashing using SHA-256, to provide a lightweight yet robust solution for ensuring data integrity without exposing sensitive data of the rehabilitated users. We compute a real-time cryptographic hash on the event of activity during the XR cognitive state change record, creating an immutable behavioural fingerprint that can be verified independently of tampered changes.

Particularly [4] introduces a signal-level data encryption and transform-based watermark of patient data; however, such an approach is mostly suitable for static biosignal or medical image data; our proposed framework extends this into cognitive-behavioural evidence to make it suitable for real-time behavioural data.

IoMT is widely recognised as the digital healthcare system for an adaptive rehabilitation approach accross Neurological and mobility impairments derived from stroke, spinal-cord injury and age-related functional disability. Early discovery [2, 15] has shown these as one of the major factors resulting in an individual's ability to carry out safe and independent activities of daily living (ADL) in real-world environments once more. Studies such as [14] have significantly contributed to the assessment of the need for a different approach to enhance support for patients with pelvic and spine alignment issues through the adaptation of various mobility systems, including walkers and canes, scooters, manual wheelchairs, and power wheelchairs. However, for wheelchair users in particular, the integration of motor control in an autonomous wheelchair for smooth navigation tasks demands a complex rule-based decision-making (RBDM), visuospatial awareness, and trust awareness in ADL cues, such as traffic signals and moving agents. The negligence of such usually increases the risk of accidents and negatively affects the quality of life. Hence, we propose a need for Trust-aware Virtual Autonomous Wheelchair Control (VAWC) and Navigation training.

Wheelchair rehabilitation and mobility training typically rely on clinic-based exercises and therapist-guided outdoor practice, which are constrained by safety risks, environmental unpredictability, limited repetition activity, and high supervision costs. Moreover, recent studies such as [2] implement an electroencephalography (EEG) based autonomous wheelchair control as an approach to overcome manual wheelchair navigational control and to streamline the cognitive stage test of the patient. However, tasks such as crossing intersections, interpreting traffic signals, and yielding to vehicles require coordinated cognitive-motor responses. This made the reliance on brain-computer interface (BCI) driven wheelchairs, where neural signals are often acquired via EEG, translate into control commands. While technically promising, such approaches face practical barriers, including signal noise, user discomfort, extensive calibration, and limited real-world scalability. These limitations have motivated growing interest in Extended Reality (XR)–based rehabilitation, such as VAWC, which enables safe, repeatable, and controllable simulations of real-time scenarios while providing objective performance measurements.

Motivated by the above reviews, this study proposes an immersive method as an alternative to invasive electrodes for autonomous wheelchair control by cognitive assessment through an observable behaviour rather than inferring user intent from neural signals. An overview of our proposed framework is presented in Figure: 1.

- We first measure the computational decision-making of the user outcome, reaction time, and motor responses within a realistic metaverse space. Combining hand tracking and spatial interaction using Meta-SDK to enable natural wheelchair control without the need for EEG caps and neural implants.

- In traffic navigation tasks, trust-aware behaviour manifests itself as the user's correct anticipation of system responses (e.g, vehicles stopping at red lights), appropriate compliance with rules, and confidence in proceeding when conditions are safe. This study proposes an applied IoMT using an XR-metaverse framework that replaces invasive neu-

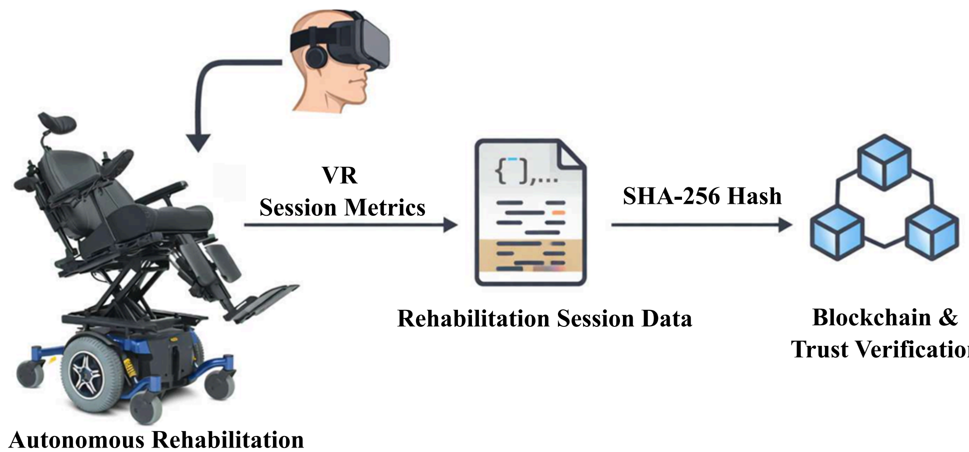

Figure 1: Illustration of our proposed Virtual Autonomous Wheelchair (VAWC) Architectural Components framework, where an immerssive autonomous experience is simulated using the core Unity Game engine and Meta SDK, and a virtual experience is perceived by the users using Meta Quest 3s VR-Headset, while the real-time performance measure of each session was visualised and stored locally in Json file and subsequently hashed using SHA-256 to enhance the trust verification and tamper-free detection on patient record.

ral monitoring with cognitive–motor behavioural assessment during a traffic navigation task.

- Subsequently, the proposed system further integrates cryptographic hashing to secure behavioural logs, enabling trustworthy record-keeping suitable for clinical auditing and future blockchain integration. By eliminating dependence on static watermark while preserving the user's cognitive objective assessment.

2. Related Work

This session reviews and focuses on three major research comparison direction as summarize in Table. 1: Blockchain Approach: Metaverse and Trust-Aware Healthcare systems, invasive BCI-Driven Wheelchair systems, and Autonomous Agents and NPCs in XR Environments.

2.1. Blockchain Approach: Metaverse and Trust-Aware Healthcare systems

The metaverse enables shared logs and data exchange through virtual environments during cognitive assessment; hence, secure data exchange and verifiable session histories remain vulnerable. Different review study such

Table 1: Comparison of Existing Rehabilitation and Trust Frameworks with the Proposed XR-Based System

Study	Primary Focus	Core Technology	Invasive	XR	Trust	Key Limitations
[2]	BCI-driven rehabilitation	EEG-based brain–computer interface	H	L	L	Requires EEG electrodes, signal noise, extensive calibration, limited real-world scalability
[3]	Mobility impairment recovery	Clinical and assistive devices	M	N	N	Lacks immersive training, no behavioral decision modeling, no digital trust mechanism
[5]	AI, VR, AR, and blockchain review	Mixed digital manufacturing technologies	N	M	M	Review-based, no concrete experimental validation
[6]	Data integrity using SHA-256	Cryptographic hashing	N	N	H	Limited to web evidence, no immersive VR or rehabilitation context
[7]	VR balance rehabilitation	Visual feedback in VR	N	H	L	Focused on posture only, lacks trust computation and traffic congestion modeling
[8]	VR and AI in stroke rehabilitation	VR, robotics, AI	N	H	L	No trust-aware logging, limited cognitive traffic decision modeling
[9]	IoMT data integrity	DCNN + SHA-256 hashing	N	N	H	Static post-acquisition medical data protection, no real-time behavioral trust
[10]	Digital evidence integrity	SHA-256 hash verification	N	N	H	Browser-based evidence logging, lacks XR interactivity and behavior modeling
[16]	Blockchain metaverse systems	Distributed ledger architecture	N	M	H	Conceptual focus, lacks human-in-the-loop rehabilitation or behavioral data capture
Proposed	IoMT-based XR rehabilitation	Hand-tracked XR + NPC traffic + SHA-256	N	H	H	Non-invasive, scalable, blockchain-ready, avoids EEG while enabling cognitive–motor assessment

Legend: H High M Medium L Low N None as [3, 4, 5] identified the high volume of data retrieved during a metaverse 3D virtual experience and how blockchain technology can provide a trust-aware encryption facilities to derive an absolute ownership control of data, hence this swiftly align with our approach and integration of cryptographical methodology such as SHA-256 to enhance data integrity and immutable approach on tampering-proof fingerprint on patient data-logs during the immersive experience.

Existing work, such as [15], explores how medical data tampered can be prevented through their proposed implementation of a cryptography method using SHA-256 hash-based detection. [4] proposed the architectural integration of Discrete Integer Wavelet Transform (DCIWT) together with SHA-256 as an approach to enhance security in the Internet of Medical Things (IoMT) data. The method was able to overcome the existing proposed [15] study, which used a watermarking technique in the protection of medical images access, tampered or and unauthorised access, which was specifical aligned with static post-study patient data, hence both studies rely on signal-domain transformation authenticity. The proposed study presents a trust-aware XR rehabilitation framework that records and verifies user decision-making directly within a real-time immersive traffic navigation task. Rather than securing medical data after collection, the system captures behavioural evidence at the point of action, logging real-time cognitive responses as users interact with dynamic traffic scenarios. This approach addresses the fundamental issues from prior SHA-256 and DCIWT-based techniques, which focus on protecting static medical records or signal-domain data. By integrating cryptographic hashing into the XR interaction pipeline, the framework validates executed intent during task performance, eliminating the need for EEG-based electrodes or signal transformation analysis.

2.2. BCI-Driven Wheelchair Systems

Prior studies on BCI-driven wheelchairs predominantly rely on EEG signals to decode user intent. These systems require precise electrode placement, extensive signal preprocessing, and subject-specific calibration. Although [2, 6, 7] already highlight the significant effective head-mounted devices (HMD) for impairment rehabilitation in laboratory conditions, the major focus of our discovery on this is that EEG-based wheelchair users suffer from susceptibility to noise, mental fatigue, and limited adoption in non-clinical settings. Moreover, most BCI systems focus on low-level directional control rather than higher-level cognitive decision-making, such as traffic compliance and limiting the assessment to a non-realistic experience focus.

2.3. Autonomous Agents and NPCs in XR Environments

The integration of autonomous non-player characters (NPCs) has been identified as a key factor in enhancing realism and user engagement in immersive environments. Recent IoMT research highlights that agent-based simulations improve situational awareness and decision-making by introducing dynamic, interactive elements that mimic real-world behaviour. To enhance user training during traffic navigation control using the hand XR-hand interactable system, rule-based and learning-based. NPCs have been used in XR for social skills training, emergency evacuation simulations [17], and driving scenarios. These agents typically follow predefined behavioural rules or simplified artificial intelligence models to ensure predictability and safety. Studies such as [8, 9, 10] have shown that predictable, rule-compliant agents are particularly important in rehabilitation contexts, as unpredictable behaviour may increase anxiety or cognitive overload in users with neurological impairments. However, the use of autonomous agents in rehabilitation-oriented XR systems remains limited. Most rehabilitation platforms either exclude NPCs entirely or use them as passive visual elements. Few systems integrate NPCs that actively obey environmental rules, such as traffic signals, and interact meaningfully with the user's navigation decisions. This limits the ADL validity of the training and reduces opportunities to dynamically assess adaptive behaviour.

In summary, the above-mentioned work discusses how IoMT patient data can be securely stored post-session activity during a rehabilitation event. The existing study also highlights how BCI and EEG are integrated into immerssive technology to ensure the authenticity of the user data.

- Unlike existing approaches, we proposed a IoMT framework integrated with XR for adaptive cognitive rehabilitation. This method overcomes the reliance on Invasive equipment and prevents the limitations on BCI, such as signal noise.

- Table. 1, highlights existing studies, including [9, 10], that implement security- and trust-oriented frameworks aimed at preventing data tampering in healthcare and IoMT environments. These studies highlight how cryptography-based mechanisms can enhance the integrity of clinical records; however, their applicability is largely confined to static medical imaging or post-session data protection. The limitation of this approach surrounded around inability to address real-time behavioural or cognitive interactions

- Our work computes a tamper-free system on real-time data during immersive activities using a cryptographic hashing method on the SHA-256 framework as an approach to overcome existing discovery reliance on wavelet transform-based security, which only focuses on static medical images. To create a medical cognitive experience during rehabilitation, we simulate a non-player computing game object using Unity game engine, and further implement and interactable hand trackin With this, we conclude a Digital medical technology framework that integrates lightweight security on patient records in real-time.

3. System Overview

3.1. Overall Framework

The proposed system introduces an Adaptive lightweight IoMT framework integrated with a Blockchain-based XR system to enhance security on patient data. We implement an interactive assessment and train cognitive-motor decision-making in users with mobility impairments, without relying on invasive BCI or EEG hardware. Instead, the framework leverages immersive XR, hand-tracking-based interaction, context-aware virtual traffic scenarios, and cryptographically verifiable logging to capture behavioural and decision-level evidence in a safe, repeatable environment. The system operates within a metaverse-style virtual urban intersection, where users navigate a virtual wheelchair through traffic signals, decision zones, and dynamic NPC to enhance the user's experience in mimic of the real world scenario to ensure effective intent and compliance are inferred through observable cognitive motor-functionality behavior (movement, stopping, reaction time) and contextual awareness (response to traffic signals), rather than neural signal acquisition.

3.2. VAWC Architectural Components

The proposed XR-based wheelchair rehabilitation system comprises three phases and is coupled with architectural modules, as illustrated in Figure: 2. The architecture integrates immersive XR interaction, cognitive–motor task coordination, secure data logging, and trust verification. With this method,

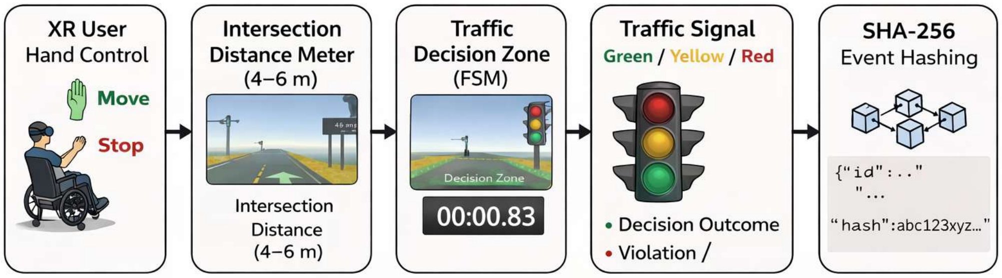

Figure 2: System flow navigation, Extended Reality-based control and trust logging.

we can carry out a rehabilitation assessment without reliance on invasive neural sensing devices.

3.2.1. Phase: XR Interaction and Sensing Layer

In this layer, we implemented a complete autonomous-based virtual control, which simulates real-world wheelchair control experience using Meta Extended Reality (XR) hand-tracking. This provides an Immerssive first-person navigation experience to the user through hand-based (open/close gesture) movement control.

3.2.2. Phase: Cognitive Traffic Decision Module

To simulate a metaverse navigation experience relatively aligned with the core system of the real-world Traffic Decision Zone (TDZ), a spatial trigger is embedded within the virtual intersection. When the user entered the decision zone, the following trials occurred:

- Trial1: The current traffic signal state (Green/Yellow/Red) is sampled.
- Trial2: The user's movement behaviour is continuously monitored using Figure: 4.
- Trial3: Reaction times were captured from the zone entry of the user to the movement response state.

With the trial state, a violation is registered upon movement during restricted signal states (Yellow/Red), enabling objective cognitive compliance assessment. The overall phases transform our immerssive traffic navigation into a cognitive task, allowing assessment of attention rehabilitation, inhibition control, and situational awareness capability, in correspondence to [2] traditionally inferred from invasive EEG-based systems.

3.2.3. Phase: Behavioural Evidence Logging and Trust Layer

Every cognitive decision event generates a structured log containing reaction time, violation status, timestamp, and session identifier. Each event is immediately processed using SHA-256 [6] cryptography hashing, which helps us produce an immutable fingerprint of the behavioural record. The cognitive logs are stored locally and structured to support merkle tree aggregation; with this, we can streamline.

- Transparent trust validation of each session.
- Tamper-proof resistant rehabilitation evidence.

3.3. Behavioral Rule of Task

We define the task rules for the rehabilitation using a *Finite State Machine (FSM)* + event logging; this approach directly extends the common point of view on traffic light rules. An approach to cognitive navigation tasks integrates locomotion control, inhibitory response training, and spatial decision-making using real-world traffic rules on IoMT framework implemented on immerssive XR environment. Our implementation enhances real-time user interaction, an effective traffication logic system, and clinical relevance of the system as an emerging approach to [2, 8] EEG-based neural decoding rehabilitation.

3.3.1. Finite State Machine (FSM) Approach

The FMS intelligence technique helps us understand the transition state changes of each patient during each immerssive cognitive task [13].

$$\mathcal{M} = (Q, \Sigma, \delta, q_0, F)$$

where: Q is the finite set of system states, Σ is the set of observable events, $\delta : Q \times \Sigma \rightarrow Q$ is the state transition function, q_0 is the initial state, F is the set of terminal states.

In the proposed task, the state set is defined as:

$$Q = \{\text{Idle}, \text{Approach}, \text{Decision}, \text{Move}, \text{Stop}, \text{Complete}\}$$

The initial state is $q_0 = \text{Idle}$, and task completion is represented by $F = \{\text{Complete}\}$.

3.3.2. Event Set and Transitions

The event set Σ consists of both user-driven and environment-driven events. Figure: 2:

$$\Sigma = \{E_{\text{enter}}, E_{\text{gesture}}, E_{\text{signal}}, E_{\text{exit}}\} \tag{1}$$

- E_{enter}: user enters the traffic decision zone ,
- E_{gesture}: hand gesture indicating movement intent,
- E_{signal}: traffic signal state change,
- E_{exit}: user exits the decision zone.

Deterministic rules govern each state transition, where:

$$\delta(\text{Decision}, E_{\text{gesture}} \wedge S = \text{Green}) = \text{Move}$$

$$\delta(\text{Decision}, E_{\text{gesture}} \wedge S \in \{\text{Yellow}, \text{Red}\}) = \text{Violation}$$

These metrics are logged only when valid FSM state transitions occur, ensuring temporal and semantic consistency of behavioural data by the real-user cognitive performance, which does not have an impact on the NPC player.

3.4. Two Layer Blockchain Trust Aware

Existing rehabilitation, such as [2, 8], used BCIs-based rehabilitation, which is based on neural signals, electrode calibration, and clinical monitoring, which makes limited auditability and trust guarantees for user sessions. To overcome this, the proposed methodology introduces a two-layer trust-aware automation that executes cognitive intent through immersive XR interaction using Meta SDK and secures session evidence using cryptographic hashing and blockchain-ready modal.

We define the XR session record event, which is hashed using SHA-256 and aggregated using a Merkle tree structure, enabling tamper-resistant users' session data verification. This layered design ensures non-invasive cognitive assessment, tamper-evident logging, Table 2, trust layers function, and future-proof compliance with decentralised systems.

Our approach system offers several improvements and new implications

- Layer-1 Cognitive Behavioural Evidence Layer (XR Event): We computed raw-data cognitive decision events generated during XR-based traffic navigation tasks. Each decision event is recorded when the user enters a Traffic Decision Zone. which were generated using the following state:

  - Traffic Signal State:

    $$S_t \in \{\text{Green}, \text{Yellow}, \text{Red}\}$$

    this represent active signal at a certain time t.

  - User Locomotion State:

    $$M_t \in \{0, 1\}$$

    The 0 signify stop of motion while 1 initiates the forward movement of the wheelchair's power using the Figure: 3.2.2 approach.

  - Change in Reaction Timely:

    $$\Delta t = t_{\text{move}} - t_{\text{entry}} \tag{2}$$

  This is the current state differences between the user's movement. With these monitored measurements, we realised the event record of each session, which is stored in JSON as featured at Figure: 1: VAWC Architectural Components correspondingly align.

  $$E_i = \{\Delta t_i, V_i, T_i, ID_i\} \tag{3}$$

  where Δt_i represents the reaction time for event i, $V_i \in \{0, 1\}$ denotes the violation indicator (movement during restricted signal states), T_i corresponds to the event timestamp, and ID_i is an anonymized session identifier.

  Our approach leverage the existing Invasive EEG-driven method, this layer directly measures *executed cognitive intent* through Meta interaction SDK within the metaverse. By observing actual user behaviour responses to real-time traffic simulated control,

- Layer-2 Cryptographic Integrity and Hashing Layer:

Table 2: Trust Properties Across Layers

Layer	Function	Threat Addressed	Trust Gain
1	Cognitive event capture	Subjectivity	Objective intent
2	SHA-256 hashing	Data tampering	Integrity

This helps us with the integrity, authentication, and non-repudiation of cognitive behavioural records generated in the XR environment. Each behavioural event aligns with Definition 3 captured at Layer 3.4 and is processed using a one-way cryptographic hash function based on the SHA-256 algorithm.

Given an event record of Equation: 3 a cryptographic digest is computed as:

$$H_i = \mathrm{SHA256}(\mathrm{Serialize}(E_i)).$$

The resulting hash H_i serves as an immutable fingerprint uniquely representing the behavioural decision event.

Due to the one-way and collision-resistant properties of SHA-256, any modification to the original event record produces a different hash value, thereby enabling reliable tamper detection. This mechanism ensures that cognitive decision logs cannot be altered without detection, even when stored locally.

Unlike encryption-based approaches, SHA-256 does not require key management and does not expose sensitive behavioural data, making it suitable for privacy-preserving rehabilitation scenarios. With this, we can transform raw XR data into cryptographically verifiable evidence, establishing a trust foundation without relying on invasive neural sensing devices.

3.5. Digital Twin and NPC Traffic Simulation

To enhance ecological validity and replicate real-world urban navigation conditions, the proposed rehabilitation framework incorporates a *digital twin-based traffic environment* coupled with autonomous non-player character (NPC) agents. This simulation transforms the XR environment from a static 2D view into a dynamic 3D Field of View, a context-aware virtual replica of real-world traffic scenarios as defined in the Figure: 3

3.5.1. Digital Twin Environment

The digital twin represents a virtual abstraction of a real-world urban intersection, including road geometry, pedestrian crossings, traffic signals, and

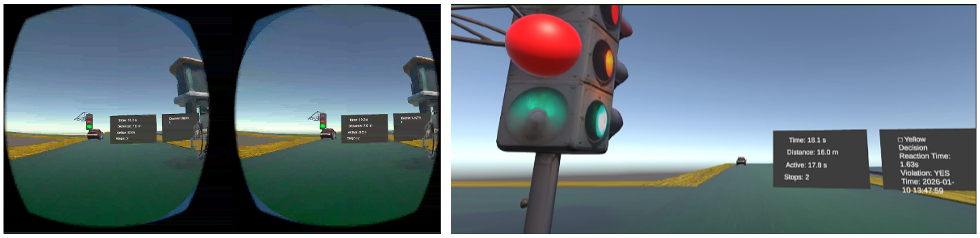

Figure 3: 3D View and Cognitive Activity Metrices Visualization

vehicle flow constraints. This virtual environment is synchronised with rule-based traffic logic rather than real-time sensor feeds, ensuring deterministic behaviour suitable for rehabilitation assessment.

This approach enables consistent replication of traffic conditions across sessions while allowing controlled manipulation of task difficulty and environmental complexity.

3.5.2. NPC Traffic Agent Modelling

Autonomous NPC vehicles are introduced to simulate realistic traffic flow and to increase cognitive load during rehabilitation tasks. Each NPC is governed by a deterministic finite state model reflecting real-world traffic compliance.

The state of an NPC agent n_j at time t is defined as:

$$X_j(t) \in \{\mathrm{Move}, \mathrm{Stop}\} \tag{4}$$

State transitions are governed by traffic signal conditions:

$$X_j(t+1) = \begin{cases} \mathrm{Stop}, & \text{if } S_t = \mathrm{Red} \\ \mathrm{Move}, & \text{if } S_t = \mathrm{Green} \end{cases} \tag{5}$$

The NPCs are constrained to predefined road segments and stop zones, ensuring adherence to traffic rules and collision avoidance. During Yellow signal phases, NPC behaviour remains deterministic to avoid introducing unpredictable hazards during cognitive assessment.

3.5.3. Restoring The Perception of sitting Cognitive

Instead of a wheelchair, we give the brain a subtle anchor perception through immerssive XR, we implement an embodiment architecture commonly used in rehab XR through META-SDK to let the user feel cognitively

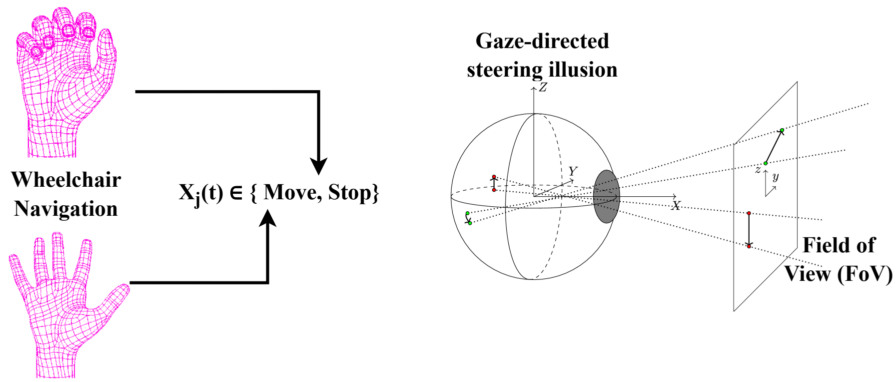

Figure 4: Gaze Directed Mobility Navigation

The Figure: 4 demonstrated how locomotion navigation were control and visualised during immerssive experience using VR-Meta Quest 3s headset, we compute *Wheelchair Navigation* using a hand-tracking method, to help the user feel movement during the rehabilitation session, while acceleration and movement brake are controlled using 4. The *Gaze-Directed Steering Illusion* follows the user's Field of View (FoV), aligning with the virtual reality 3D X, Y, Z dimensional experience. The experience was made realistic by steering control using the user's Gaze direction during movement.

on an autonomous rehabilitation wheelchair, as demonstrated in Figure: 1, while sitting. The constraining locomotion to the horizontal plane/ground preserves ground-referenced proprioception, enabling stroke survivors to experience moving mobility without inducing vestibular conflict. The forward locomotion was controlled via hand Figure: 4, openes and constrained to the horizontal plane by supressing vertical displacement in the head-forward vector.

4. Experimental Evaluation and Result

4.1. Experimental Implementation

The experimental implementation was designed to validate our proposed IoMT-based XR rehabilitation framework. The system integrates interactable, rule-based traffic decision logic and secure behavioural event logging to evaluate cognitive-motor responses without invasive neural sensing.

i. Cognitive Task

Our task approach integrates locomotion control inhibitory response training, and spatial decision using real-world traffic rules in an immerssive XR environment, were user perceive the yellow signal, decides to stop or continue cognitive movement and execute motor functionality action using Equation 4 (open or close hand). We define the *task rules* to validate the rehabilitation goal beyond normal traffic light rules by considering the *reaction-time, impulsivity vs caution, motor inhibition, cognitive anticipation*

- **Rule A** When yellow appears, and the wheelchair is within X meters of the intersection *4-6 meter*, this forces an anticipation of action and not a memorised action.
- **Rule B** Our experimental clinical cognitive task uses wheelchair safety training through FoV gazing control, movement measurement was derived using *reaction-time = time(from yellow ON - movement STOP*, *violation = moved during red.* and *anticipation = stopped before red.*

ii. Time Metrics Evaluation

The proposed approach uses a coroutine traffic-controlled sequence as a time-based method and is not dependent on tasks; this enables us to correspond a contextual and unpredictable timing on traffic light changes, to leverage train memorisation on fixed. To ascertain this, we compute a *Random time trains cognitive* introducing a time-critical anticipatory decision-making task.

iii. Adaptive Control Smoothness

The goal target where dynamically repositioned relative to head orientation, gaze-directed locomotion, a key component of natural walking and powered automated wheelchair navigation, to compute the XR-based hand movement control, where Figure: 1 Autonomous rehabilitation wheelchairs were controlled based on the Equation. 4 as an approach to make the participant feel immerssive and in self control of the wheel during the cognitive trial, we implement a VR based clinical visualisation functional mobility on Gaze-directed mobility for steering illusion control, wheelchair navigation with walking intent using the user hand, through which an open-hand compute move/accelation, while the close-hand compute stop/break as shown in Figure: 4, and the Field of View (FoV) been controlled in correspondent of 3D (x,y,z) dimentional perspective position to make make the users feel virtual immersive experience.

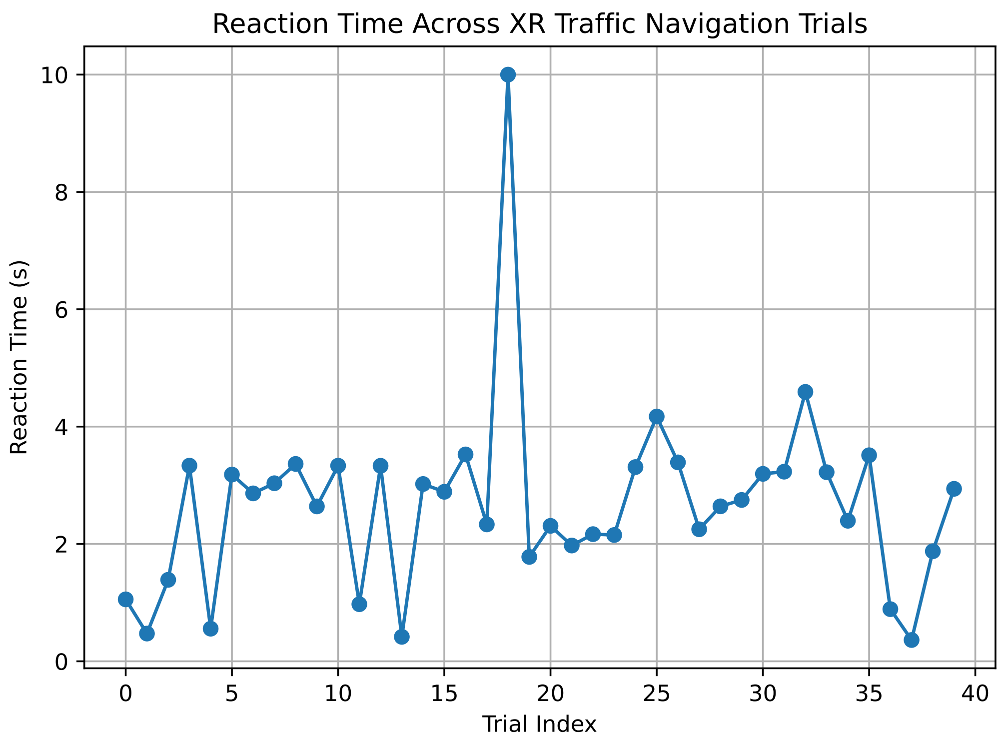

Figure 5: Reaction Time Across XR Traffic Navigation Trials

4.2. Result Evaluation

The IoMT system was implemented using Unity XR and deployed on a Meta Quest headset with hand-tracking-based locomotion control. Participants navigated a virtual wheelchair through a digital twin urban intersection containing traffic signals and autonomous NPC vehicles. Each experimental session consisted of multiple traffic decision trials, during which behavioural data were recorded automatically. For each trial, reaction time, movement behaviour, traffic-rule compliance, and timestamps were logged locally in structured JSON format. Selected events were additionally hashed using SHA-256 to enable integrity verification and blockchain-ready aggregation.

4.2.1. Reaction Time Analysis

We compute reaction time as the dynamic state difference between entry into the Traffic Decision Zone and the initiation of movement or inhibition. Figure: 5 illustrates reaction time across successive XR navigation trials.

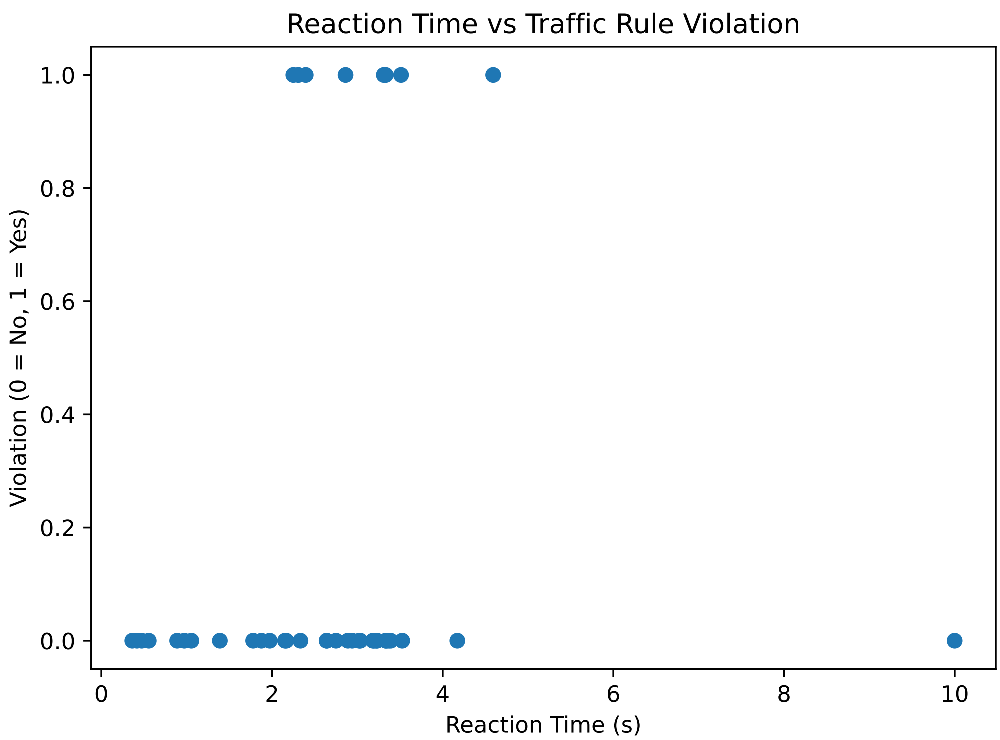

Figure 6: Reaction Time vs Traffic Rule Violation

Indicating stable user engagement and reliable task execution on over 40 trials conducted on average of 10(s) between each Illustration. 1 of each change in event status. Figure: 6 outlined the relationship between reaction time and traffic rule violations during XR-based navigation tasks. Each point represents a discrete cognitive decision event. Non-violations cluster within lower reaction times of $\tilde{0}.4$–3.5 seconds, while violations mainly occur at delayed responses, indicating impaired inhibitory control. This observation help us overcome the existing EEG-based [2, 9] approach by measuring actual movement decision without reliance on any external calibration devices, using direct behavioural evidence of virtual reality as IoMT, enabling objective assessment without reliance on neural sensing devices.

4.2.2. Traffic Rule Compliance

We evaluated the traffic rule using the violation Equation:4 indicator, where $V_i = 1$ denotes movement during restricted traffic signal states. Figure:

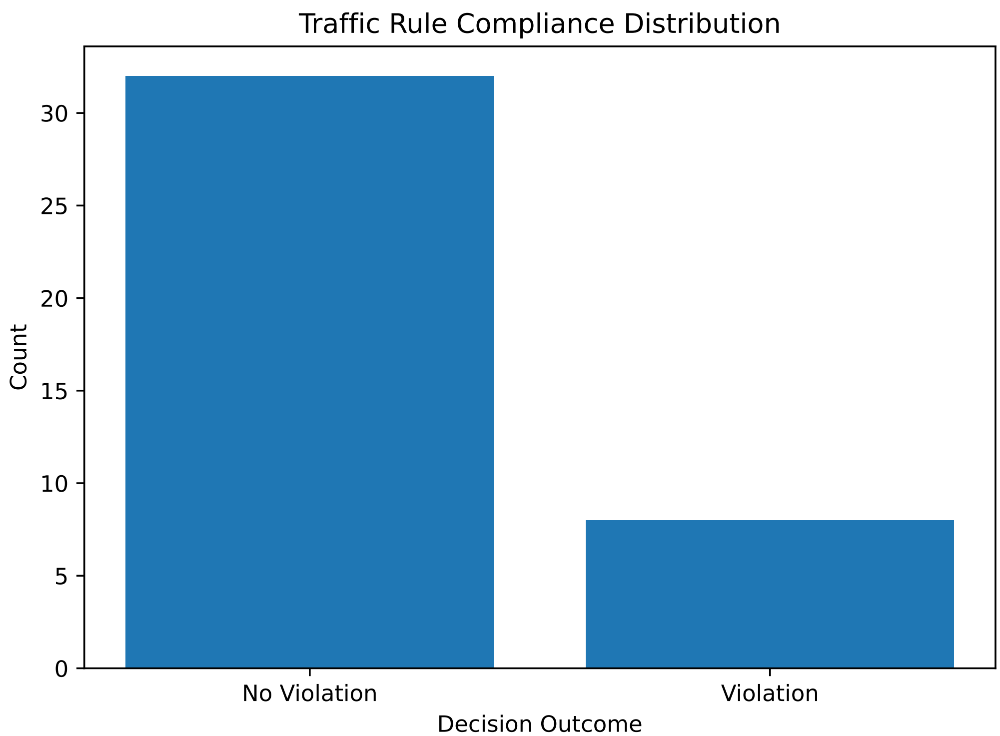

Figure 7: Traffic Rule Compliance Distribution

6 presents the distribution of compliant versus violation trials. The majority of trials resulted in compliant behaviour, while violations occurred primarily under increased cognitive conditions. This demonstrates the system's ability to objectively capture inhibitory control failures without reliance on invasive neural sensing. The XR hand tracking was computed to evaluate the real-time trajectory compliance of the user, as shown in the Figure: 7 illustrates the most common traffic rule compliance metrics on a count of 40 trails significantly demonstrating improvement of trial cognitive performance by the user on subsequent session, this differences in non-violation show an average of 30, while violation shows a significant reduction of 10 average, making the proposed cognitive rehabilitation widely clinically adaptive.

4.3. Blockchain-Based Integrity Validation

The cryptographic implementation served as a guaranteed tamper-resistant safeguard for the cognitive event; the authenticity of the patient session

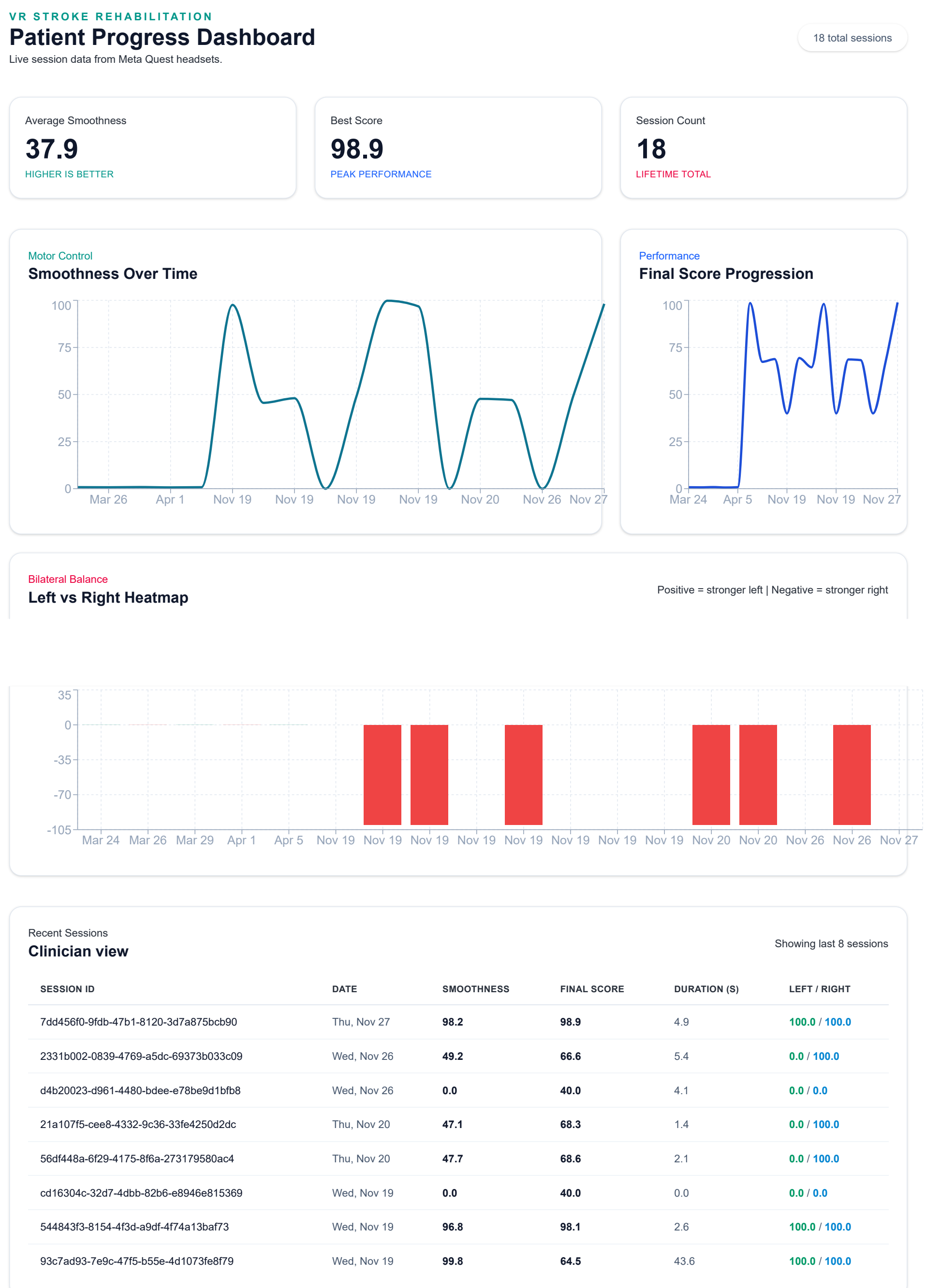

Figure 8: Patient Progress Dashboard Visualising XR-Based Rehabilitation Metrics derived from real-time data capture, and Cryptographically Logged Behavioural Events. Dashboard available at: Progressive Web Application VR Rehabilitation Dashboard

record is verified by loading section data and recomputing using SHA-256, while comparing with the real-time user's data as demonstrated at Figure: 8 (cognitive live session data from Meta Quest 3s) captured during the execution time using verification logic such as event_original and event_stored as raw cognitive data for determining tampered or accurate data. The event_origin log of Time:22.9 seconds, on an intersection distance as shown Figure: 3 of 22.4 meters between the decision zone of Figure: 2 FSM while the active_time record of the session based on time participant spent on cognitive activity is considered as the event original and the violation status directly triggeed the event stored hashing computation status, which inflect notarize patient session cognitive session data immutable in real-time. The derived result shows that the cryptographic implementation served as a guarantee for the following properties:

Table 3: Blockchain Integrity result validation impact

Property	**Achieved**	**Section result**
Integrity	Yes	Trust in Digital
Tamper detection	Yes	Hash Consistency (100%)
Patient Privacy	Preserved	Ethical Compliance

5. Conclusion and Future Work

This paper presented a trust-aware IoMT based on a metaverse XR framework for autonomous adaptive rehabilitation and traffic navigation training that replaces invasive EEG-based intent inference with embodied cognitive-motor behavioural assessment. By integrating immersive XR interaction, finite state machine-driven task logic, digital twin traffic modelling, autonomous NPC agents, and cryptographic trust mechanisms, the proposed system enables objective, tamper-free data security, repeatable tasks, and non-invasive evaluation of cognitive decision-making.

Experimental results demonstrated reliable measurement of reaction time and traffic-rule compliance, increased cognitive engagement in the presence of NPC traffic, and effective tamper detection through SHA-256-based integrity validation. The system successfully captures executed intent within realistic navigation scenarios while preserving user privacy through local data storage and blockchain-ready cryptographic aggregation. Hence there is a need of extended an haptic wearable arm control lightweight, to leverage more realistic experience control on IoMT rehabilitation, future work can extend the usage of NFT data decentralisation approach to streamline more security on user data.

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