

**Gamified VR-Based Therapy System for Upper Limb
Rehabilitation in Children with Hemiplegia**

25-26J-472

Project Proposal Report

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B.Sc. (Hons) Degree in Information Technology specialized in
Software Engineering

Department of Software Engineering

Sri Lanka Institute of Information Technology

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Research Component: Wrist Movement Tracking

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DECLARATION

We declare that this is our own work, and this proposal does not include without acknowledgement any material already presented for a degree or diploma in any other university or higher education institute and to the best of our knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Wrist mobility is a fundamental component of upper limb functionality, playing a crucial role in performing daily activities such as grasping, manipulating objects, and coordinated hand-arm movements. Impairments in wrist motion, whether resulting from neurological disorders like hemiplegia following childhood stroke or cerebral palsy, traumatic injuries, or post-surgical recovery, can severely compromise an individual's independence and quality of life. Children with hemiplegia particularly face significant challenges as their affected upper limb often exhibits reduced range of motion, weakness, and impaired motor control, directly impacting their ability to perform age-appropriate activities and potentially affecting their developmental progress. Traditional rehabilitation approaches, while clinically proven, frequently encounter substantial limitations, including low patient engagement due to repetitive and monotonous exercises, inconsistent feedback mechanisms that fail to provide real-time performance evaluation, limited personalization that does not adapt to individual progress rates or emotional states, and restricted accessibility due to the need for frequent clinical visits and specialized equipment.

This research proposes an innovative wrist movement tracking system that integrates advanced wearable sensor technology with a gamified Virtual Reality (VR) therapy environment specifically designed to address the rehabilitation needs of children with hemiplegia. The system employs high-precision Inertial Measurement Unit (IMU) sensors strategically positioned on the wrist to capture comprehensive motion data in real-time, including linear acceleration, angular velocity, and magnetic orientation across all movement planes. The captured sensor data is transmitted wirelessly to a sophisticated processing module that utilizes advanced machine learning algorithms, specifically Long Short-Term Memory (LSTM) networks for temporal sequence analysis and Support Vector Machines (SVM) for robust classification, to accurately identify and classify four primary wrist movements: flexion, extension, pronation, and supination. The classified motion data is seamlessly integrated into an immersive VR-based therapy game environment that provides immediate visual and auditory feedback, creating an engaging "catch fish" rehabilitation activity where wrist movements

directly control game interactions. The system incorporates adaptive difficulty adjustment mechanisms that monitor user performance metrics, emotional state through physiological indicators, and fatigue levels to dynamically modify game challenges, ensuring optimal therapeutic benefit while maintaining high engagement levels throughout rehabilitation sessions.

The proposed solution addresses critical gaps in current rehabilitation technology by offering a comprehensive, modular, and cost-effective platform designed for deployment in diverse settings including physiotherapy clinics, home-based rehabilitation programs, and telemedicine applications. The system provides clinicians with a sophisticated dashboard featuring detailed analytics on patient progress, movement quality assessments, therapy compliance rates, and objective performance metrics that can be correlated with standardized clinical assessment scales. Expected outcomes include improved wrist range of motion and motor control in pediatric hemiplegia patients, increased therapy compliance through gamification, enhanced clinical decision-making through data-driven insights, and reduced healthcare costs through enabling effective home-based rehabilitation. The modular architecture allows for future expansion to include additional upper limb joints, integration with other therapeutic modalities, and customization for various neurological conditions, positioning this research as a foundation for next-generation rehabilitation technology that combines clinical efficacy with patient engagement and accessibility.

Keywords: Virtual Reality, Wrist mobility, Upper limb functionality, Hemiplegia, Childhood stroke, Wearable sensor technology, Machine learning, Wireless data transmission, Embedded systems

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LIST OF ABBREVIATIONS

Abbreviation	Description
ML	Machine Learning
IMU	Inertial Measurement Unit
SDLC	Software Development Life Cycle
VR	Virtual Reality

1. INTRODUCTION

Wrist range of motion is an important aspect of upper limb function as it is an important bridge between the movements of the forearm and fine intricate control of fingers. The wrist joint complex anatomical structure allows four basic movements such as flexion, extension, pronation and supination that are crucial for achieving accurate placement and overall orientation required for efficient manipulation of objects, clutching movements and integrated hand-arm activities [1]. These motions are essential for essential activities such as turning door handles, pouring a cup of water, using a fork and knife and for the play activities that are fundamental to child development.

Hemiplegic children (those who have hemiplegia as a result of a childhood stroke, cerebral palsy or traumatic brain injury) experience severe wrist motion control impairments that severely degrade their quality of life and independence [1]. It is a relatively common condition found in around 1 in 1,000 children that affects the upper (distal) limb and is generally characterized by weakness or paralysis on one side of the body, particularly involving the distal joints of the upper limb (i.e. the wrist). The wrist may experience decreased range of motion, loss of motor control and muscle strength, and the adoption of compensatory movement patterns, which in turn can cause problems such as postural deviations and bone density reductions [2]. These impairments severely compromise a child's ability to

perform age-appropriate bilateral activities, potentially affecting their developmental progress, academic performance, and social integration.

Conventional wrist rehabilitation strategies suffer from large limitations that prevent optimal therapeutic make use of despite being clinically established. Traditional therapy approaches involve exercise paradigms where patients must do the same routine exercises over and over, requiring them to directly interact with a physical therapist, which may not be engaging due to their repetitiveness [2]. Children, especially, tend to loose interest during classical rehabilitation and as a consequence to comply with less satisfactory rehabilitation results. Furthermore, traditional methods also lack objective feedback mechanisms, and it is difficult for both the therapist and the patient to quantitatively evaluate the progress and adjust the treatment program. The reliance on subjective clinical assessments and the lack of real-time performance metrics further compound these limitations, while accessibility constraints due to geographical barriers, healthcare costs, and limited therapist availability in regions like Sri Lanka create additional challenges for consistent therapy delivery [3].

Recent developments in wearable sensor technology, notably Inertial Measurement Units (IMUs), have provided opportunities for objective, real-time tracking of wrist movement and rehabilitation [5]. IMUs combine accelerometers, gyroscopes, and magnetometers and record a complete set of motion data from SO across all planes of movement, offering detailed wrist kinematic information which includes wrist position, orientation as well as velocity. In conjunction with advanced machine learning models like Long Short-Term Memory (LSTM) networks for temporal pattern learning and Support Vector Machines (SVMs) for robust movement classification, desired wrist movement can be accurately detected and classified in real-time, facilitating automated assessment and feedback in rehabilitation [5][6].

The upcoming utilization of sensor technology integrated with wearable devices within Virtual Reality (VR) therapy environments is a game changer in

the field of pediatric rehabilitation, changing routine movements into fun, engaging, optimized exercises [7]. The VR-based therapy devices have the capability to exhibit the visual and audio feedback which fully corresponds to the arm motion, so that “catch fish” game activities control the VR avatar by using the wrist flexion and extension [9], [10]. Such an approach meets the growing demand for more active patient involvement and the need for objective quantifiable information regarding therapeutic progress.

Despite these technological improvements, there are still notable deficiencies in current wrist rehabilitation systems. Most current methods are limited to single-joint tracking instead of full integration with the upper limb, do not involve emotion-adaptive feedback (i.e., being adaptive to the tracking difficulty based on the user's psychological status) and have limited clinical decision-support, such as remote therapy prescription and monitoring in tele-therapy [4],[5]. In addition, few systems have been developed with this objective, specifically for the pediatric population with hemiplegia, and that is crucial, as the interface and engagement strategies must be adapted to their age [9].

The proposed wrist motion tracking system uses a systematic validation setup in order to define trustful baseline values and to allow for reliable therapeutic monitoring. The method starts with the collection of data of typically developing children in order to obtain the norms of hand movement patterns over age and development [12],[13]. This reference dataset contains elements of natural variability in wrist flexion/extension, and pronation/supination ranges, and movement velocities and patterns that provide reference standards for the machine learning classification algorithms. Once the baseline is set up, the validation procedure includes a three level method and it was specifically developed for hemiplegic children. First, the uninvolved (normal) hand of children with hemiplegia is tested and compared to the normative data resource of healthy children. This comparison provides information regarding whether the uninvolved extremity exhibits movement patterns that fall within a normal range of typical

development, considering the possibility of bilateral influences that may occur in hemiplegia [14]. There is evidence that the 'unaffected' side in children with hemiplegia also demonstrates subtle movement differences compared to typically developing children which further supports comparison to typically developing controls. If the unaffected hand demonstrates movement patterns consistent with typical development (within 1-2 standard deviations of the normative dataset), it serves as the primary reference for assessing the affected limb, enabling personalized rehabilitation goal-setting based on the child's individual motor potential [16]. However, when the unaffected hand shows significant deviations from typical patterns, indicating potential bilateral involvement, the normative dataset from typically developing children becomes the primary reference standard [17]. The affected wrist is then systematically compared against the established reference (either the child's unaffected hand or the normative dataset) to quantify movement deficits, identify specific movement impairments, and establish individualized therapy goals [2][9].

This research element seeks to overcome these limitations by developing a novel wrist motion tracking system, consisting of high-accuracy IMU sensors, machine learning based motion classification, and adaptive VR -based therapy games [5]. The system is uniquely developed for children with hemiplegia, using emotion detection to aim therapy towards the interests of the child, to also provide performance feedback during game play and to aid monitoring of clinical progress [9]. By targeting the wrist as a key element of upper limb rehabilitation, this work is not only advancing an overall multi-joint rehabilitation system, but is focused on the biomechanical and therapeutic needs of wrist motor recovery in pediatric hemiplegia. The proposed wrist tracking component represents a significant advancement in rehabilitation technology by offering a cost-effective, engaging, and clinically validated approach to wrist rehabilitation that can be deployed in both clinical and home-based settings, ultimately improving therapeutic outcomes and quality of life for children with hemiplegia [2][7].

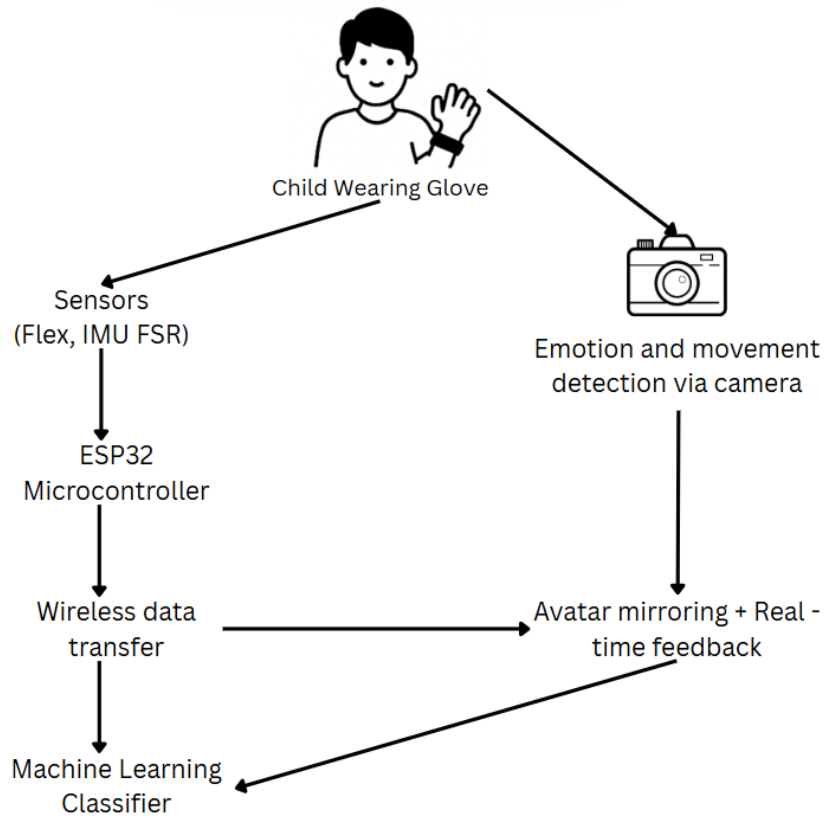


Figure 1.1: Overview Diagram

1.1 Background & Literature survey

Hemiplegic-wrist dysfunction is a major obstacle, which disables children with hemiplegia, as the wrist plays a pivotal role in linking proximal arm usage with distal manual skills necessary for life's activities. The wrist, unlike other upper extremity joints, needs to be stable for power grip tasks (i.e., a prehension form that uses the largest muscles, such as pronated grasp with elbow flexion) and mobile for finer positioning required elsewhere [1]. The complexity of biomechanics of the wrist, with its radiocarpal and midcarpal joints that must be coordinated among a number of degrees of freedom, makes it difficult to rehabilitate when neurological control is disrupted. Traditional wrist rehabilitation approaches in pediatric hemiplegia have primarily focused on passive range of motion exercises and constraint-induced movement therapy protocols, but these methods often fail to address the specific motor control deficits and compensatory patterns that develop in the wrist joint [2].

The application of virtual reality technology specifically for wrist rehabilitation has shown promising but limited results in pediatric populations. While systematic reviews demonstrate VR's potential to increase therapy engagement and provide modest improvements in upper limb outcomes, most studies have focused on gross motor movements rather than the precise wrist control patterns essential for functional hand use [7][8]. The few studies that have specifically targeted wrist movements in VR environments have primarily involved adult stroke populations, with limited evidence for pediatric applications [9]. Action-observation therapy programs like Fun 'n' Games have incorporated some wrist-specific activities, but these remain largely non-technological approaches that lack objective measurement capabilities and real-time feedback mechanisms essential for motor learning [3].

Inertial Measurement Unit (IMU) technology is the most suitable methodology for wrist movement tracking when considering the intricate kinematics of the joint and the requirement for non-invasive measurement during functional tasks. Studies focused on IMU-based wrist tracking, there are evidence showing that these sensors can properly record flexion, extension, radial deviation, ulnar deviation, pronation and supination with enough accuracy for clinical purposes [5]. However, there are also wrist specific drawbacks: the placement of sensors is sensitive due to the proximity of the joint to the hand, the heightened susceptibility to motion artifacts from active finger movements and more sophisticated calibration methods are needed to exponentiate biological anatomical individuality [18]. Studies have shown that dual IMU configurations, with sensors placed on both the forearm and hand, provide superior tracking accuracy compared to single-sensor approaches, though this increases system complexity and potential user burden [19].

Machine learning applications models for wrist movement classification are particularly challenging compared to other upper limb joints, due to the delicacy of many wrist movements and the large degree of coupling between these movements and finger and wrist motions. Recently, it has been shown that when trained on the appropriate dataset, LSTM networks are capable of accurately classifying simple wrist movement (flexion/extension, pronation/supination) with a classification accuracy over 90%; however, classification performance drops significantly for higher function movement patterns [20]. Support Vector Machine approaches have shown particular promise for real-time wrist movement classification due to their computational efficiency and ability to handle the high-dimensional feature spaces typical of multi-axis IMU data [21]. However, most existing studies have focused on discrete movement classification rather than the continuous movement assessment required for therapeutic applications.

Integration of wrist-oriented motion tracking with VR-therapy games still both opens up new possibilities as well as challenges not seen to the same extent

for other joints. Because the wrist plays a role in hand orientation, VR interactions should find a compromise between high precision and motor limitations in hemiplegia. It has been demonstrated that VR games with isolated wrist motion can be used to increase ROM and motor control, however, compensatory strategies that children with hemiplegia often use need to be considered in game design [22]. The "catch fish" game paradigm, where wrist flexion and extension control virtual object manipulation, has shown particular promise in preliminary studies, though optimal difficulty progression and feedback mechanisms remain under investigation .

Existing wrist rehabilitation technology is constrained by the absence of validated assessment protocols specific to the pediatric population, inadequate knowledge pertaining to the optimal site of sensors for various wrist movement patterns, and limited use of emotion-adaptive feedback for the purpose of wrist rehabilitation activities. The majority of the wrist tracking systems published worldwide operate as stand-alone devices and not within a complete upper limb robot-rehabilitative scenario leaving their clinical applicability underwhelming [5],[6]. In addition, the mathematical modeling demands of clinician dashboards for wrist rehabilitation metrics are drastically different than other joints as both general movement quantity and quality parameters specific to wrist movement need to be tracked. While emotion detection and affective sensing technologies are being explored for general rehabilitation applications, their specific application to wrist-focused therapy activities remains largely unexplored, representing a significant gap in the development of personalized, adaptive wrist rehabilitation systems.

1.2 Research Gap

Despite previous research focusing on specific elements (immersive task practice, virtual reality or game-based therapy, IMU-based monitoring, machine learning-based movement analysis, etc.), several areas still require improvement:

- **Limited pediatric-specific wrist movement normative data and validation protocols.**

The majority of previous research on wrist biomechanics and movement patterns primarily examines adult populations, notably lacking normative data for typically developing children of various ages [18][19]. This deficit is particularly concerning when creating protocols for assessing pediatric hemiplegia, since assessing baselines is key to developing therapeutic aims as well as measure progress. The assessment processes that are current clinical practice rely primarily on subjective observation, and basic measures of angles (i.e., goniometry), which are not always standardized, lacking the granularity and rigor modern rehabilitation technologies require for validation [2].

- **Inadequate sensor integration and placement optimization for pediatric wrist tracking.**

While IMU-based motion capture has shown promise for adult applications, limited research addresses the unique challenges of sensor placement and calibration in pediatric populations [5][6]. Children's smaller anatomical structures, growth-related changes in limb proportions, and reduced tolerance for bulky equipment create specific technical challenges that remain largely unaddressed in current literature. The optimal sensor configuration for capturing the four primary wrist movements (flexion, extension, pronation, supination) while minimizing interference from coupled finger and forearm motions has not been systematically investigated in pediatric populations [20].

- **Insufficient machine learning models specifically trained for pediatric wrist movement classification.**

Although IMU-based motion capture systems have demonstrated its efficacy for adult use, few studies have explored the different challenges regarding sensor

placement and calibration in pediatric populations [5][6]. These challenges include children's smaller anatomical structures, differences in the proportion of limbs due to growth, and lesser tolerance levels to bulky devices, among others; it remains unclear if these technical challenges have been accounted for in the existing research. The empirical evidence regarding the best placement of sensors for capturing each of the four main wrist motions (flexion, extension, pronation, supination) while minimizing signal interferences due to coupled finger and forearm motions is absent in pediatric populations [20].

- **Limited VR game design frameworks tailored for wrist-specific therapeutic interventions.**

Although VR technology has shown promise in rehabilitation for the upper limb, many current games focus largely on gross motor movement, with limited modifiability to wrist control patterns (which are necessary for functional activity) [7][8]. The "catch fish" game paradigm and other games or activities designed to use wrist control are not constructed using consistent design principles and do not consider motor deficits, attention spans, motivation factors related to children with hemiplegia [22]. Many VR rehabilitation games also do not provide the appropriate difficulty progression for wrist movements as the control changes are of a finer scale than those associated with shoulder or elbow movements.

- **Absence of emotion-adaptive feedback systems specifically designed for wrist rehabilitation activities.**

While affective computing has been explored for general rehabilitation applications, its specific implementation for wrist-focused therapy remains largely unexplored. The subtle nature of wrist movements and their frequent integration with cognitive tasks during VR interactions create unique requirements for emotion detection and adaptive feedback that differ substantially from other upper limb joints. Current emotion-adaptive systems lack the specificity required to adjust wrist rehabilitation tasks based on patient psychological state, fatigue levels, and engagement metrics.

- **Inadequate clinical integration and validation frameworks for wrist-specific rehabilitation technology.**

Most current wrist tracking systems are implemented as standalone research prototypes and not as clinically integrated tools, limiting their usefulness in therapeutic practices [5][6]. The lack of standardized wrist rehabilitation outcome metrics, particularly measures that can be automatically derived from sensor data and be related to clinical assessment scales, is a major barrier to clinical integration. Also, clinical dashboard outputs monitoring wrist rehabilitation cause further diverging requirements of clinical dashboard outputs from rehabilitation of other joints because it requires user feedback of movement quantity and quantity measures of wrist biomechanics as an output specific to wrist rehabilitation progress.

- **Limited understanding of optimal therapeutic dosing and progression protocols for technology-enhanced wrist rehabilitation.**

Although existing therapies inform exercise progression in wrist rehabilitation, the best way to introduce sensor feedback, virtual reality (VR) engagement, and difficulty gradation for pediatric applications is not known [2]. There is also no systematic investigation into the relationship between technology-enhanced wrist exercises and functional outcome benefits or rehabilitation effects such as whether trained movements were transferred to activities of daily living in children with hemiplegia.

These identified gaps collectively demonstrate the need for a comprehensive, pediatric-specific wrist movement tracking system that addresses the unique technical, clinical, and therapeutic requirements of this population while providing the foundation for evidence-based, technology-enhanced rehabilitation interventions.

Research / System	Wrist-Specific Movement Tracking	Wearable IMU/Flex Sensors for Wrist	Machine Learning–Based Motion Classification	VR/Gamified Wrist Therapy	Emotion-Adaptive Feedback for Wrist Activities	Wrist-Specific Clinical Metrics & Monitoring
Andersen et al., 2013 [2] - Intensive Upper Extremity Training	✓	X	X	X	X	X
APCP, 2020 [3] - <i>Fun 'n' Games</i> Play-Based Therapy	✓	X	X	X	X	X
Filippeschi et al., 2017 [5] - IMU Motion Tracking Survey	Partial (Focus on specific joints)	✓	X	X	X	X
2021 [6] - Wireless Motion Capture for Upper Limb Rehab	Partial (elbow/wrist focus)	✓	X	X	X	X

Öhman, 2022 [4] – Gamified Upper Limb Rehab	Partial (single or few joints)	✓	Partial (simple classification)	✓	X	X
Proposed System	✓	✓	✓	✓	✓	✓

Table 1.1: Research Gap Analysis

1.3 Research Problem

Hemiplegia is a neurological condition that results in paralysis or severe weakness of one side of the body, most commonly caused by early childhood stroke or cerebral palsy. Children with hemiplegia often experience restricted or uncoordinated movement in their upper limbs, which significantly affects their ability to perform daily activities such as reaching, grasping, and holding. Clinical evidence supports the idea that early and consistent rehabilitation can help restore function through neuroplasticity. However, in practice, access to regular therapy is limited, especially in countries like Sri Lanka, where therapist availability is scarce, travel for therapy is costly, and adherence is low due to therapy being monotonous or demotivating for children.

Recent research shows that gamified rehabilitation, games to validate sensor-based movements, and virtual reality (VR) may be key innovations to increase engagement and improve the accuracy of rehabilitation. Yet, as the research and evidence also show, most systems are designed only for older adults, are generally too expensive, or require complicated robotic hardware and equipment that may only be available through overseas purchases. With significant technology and economic barriers, there is a substantial research and implementation gap in developing an affordable, real-time, engaging, and child-friendly system specifically for children with unilateral motor deficits.

This project proposes a low-cost, wearable VR-based therapy system for hemiplegic children, using sensors and machine learning to monitor upper limb movement in real-time. It provides corrective feedback through a gamified VR environment, adapts to emotional states, and is designed for affordable use in both clinical and home settings in Sri Lanka.

2 OBJECTIVES

2.1 Main Objective

Design and develop a comprehensive wearable wrist movement tracking system that integrates real-time motion sensing, machine learning-based movement classification, and adaptive VR-based therapy games to enhance upper limb rehabilitation outcomes specifically for children with hemiplegia.

2.2 Specific Objectives

Integrate wearable sensors for wrist movement tracking.

- Research and select appropriate sensors (IMU sensors, Flex sensors) for wrist joints.
- Design and build hardware integration for wrist movement tracking using ESP32/Arduino + breadboard + IMU sensors.
- Support tracking of 4 main wrist movements.

Implement a VR-based therapy game focused on wrist-based exercises.

- Map sensor data to wrist motions (e.g., flexion, extension, pronation, supination)
- Develop VR-based therapy activities focusing on wrist mobility (e.g., "catch fish" game)
- Create an adaptive VR game that adjusts difficulty according to wrist movement performance.

Train a ML model on wrist motion classification

- Collect wrist movement data and label it for training.
- Train a machine learning model (e.g., SVM, LSTM) to classify wrist movements.

- Implement real-time motion pattern recognition for wrist-specific exercises.

Implement an adaptive feedback system.

- Add adaptive feedback based on performance and emotion detection input related to wrist movements.
- Integrate the wrist-related game component into the overall mirror therapy system.
- Provide real-time visual feedback to users on wrist movement quality and execution.

3. METHODOLOGY

3.1 Understanding the Research Domain

3.1.1 Wearable Sensor Technology

Wearable sensor technology is the basis of this area of research, focusing specifically on Inertial Measurement Units (IMUs) and flex sensors to measure wrist movements. IMUs have accelerometers, gyroscopes, and magnetometers for linear accelerations, rotation rate, and the orientation of the magnetic field, respectively. These three sensor types can track wrist joint movement together (e.g., flexion, extension, pronation, and supination) for overall motion tracking. Each sensor type comes with a different modality and this combination of different sensor types can offer motion capture that is less sensitive to either individual sensor drift or interference from the surrounding environment.

3.1.2 Machine Learning for Motion Classification

Machine learning techniques, specifically supervised learning algorithms, such as Support Vector Machines (SVM) and Long Short Term Memory (LSTM) networks, were used to classify wrist movement patterns. LSTM networks are ideally suited for sequential motion data as they can model sequential dependencies in movement sequences and are therefore more appropriate for the classification of complex wrist motion patterns. SVM algorithms provided good classification performance for the discrete location categories, and coupled with the right kernel functions, can also manage high-dimensional sensor data.

3.1.3 Virtual Reality Game Development

Virtual Reality (VR) technology is the main interface that provides a therapeutic technique via immersive and gamified experiences. VR game development, utilizing tools such as Unreal Engine, allows for the development of "fun" therapeutic activities targeted specifically for wrist rehabilitation. The VR space

can provide instant visual feedback based on sensor input and the game can interact with the user to adapt the therapy session based on movement patterns and feedback gathered from user performance metrics.

3.1.4 Embedded Systems and Real-Time Processing

The wrist tracking segment necessitates embedded systems architecture leveraging microcontrollers and microcontroller platforms (such as ESP32 or Arduino) for real-time sensor data acquisition and processing. Specifically, these systems must handle continuous data streaming, data fusion algorithms (sensor fusion), and wireless communication protocols to send movement data to a processing unit with minimal delay. Timely constraints are crucial for instantaneous feedback during therapy.

3.1.5 Signal Processing and Sensor Fusion

Advanced signal processing methods, including filtering (Kalman filters, complementary filters) and sensor fusion, are crucial when reconstructing motion from raw sensor data. These algorithms improve tracking accuracy during sessions, while minimizing the impacts of sensor drift, noise and/or environmental factors.

3.1.6 Microservice Architecture

Microservice architecture is a variation of the service-oriented architecture structural style described in software engineering. It is an architectural pattern whereby an application is presented as a set of fine-grained, loosely-coupled services that communicate with one another using simple protocols. A microservices architecture disaggregates a program into a collection of small services that communicate with one another over an established set of lightweight protocols (e.g., stream-based communications or RESTful APIs). Common characteristics and key benefits Microservices architecture represents "componentization using services," which increases flexibility and scalability; "therefore they are structured around business capabilities," it is easier to simplify and read the code; "infrastructure automation" for DevOps and continuous

delivery; and "decentralized governance and data management," which allows polyglot persistence, which supports suitability and flexibility, etc.

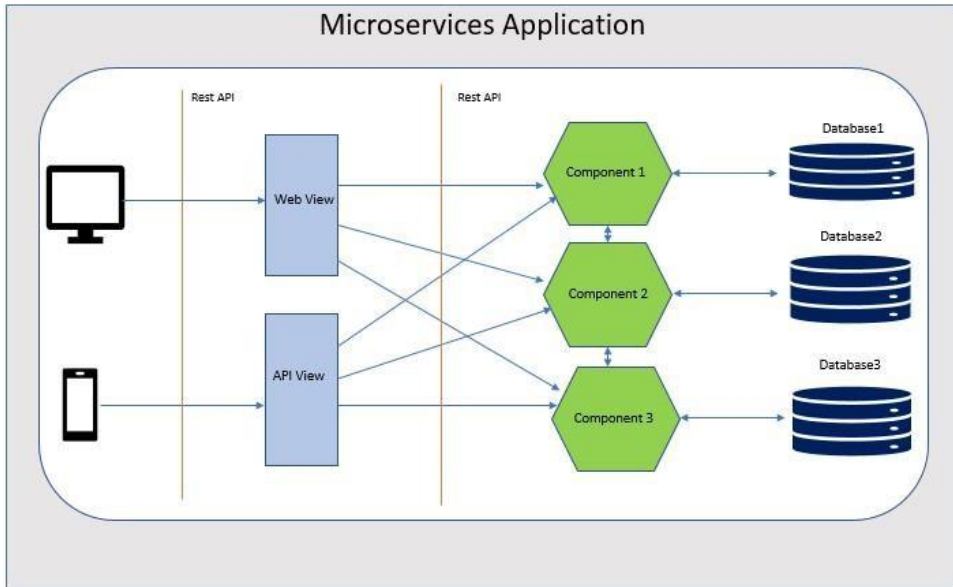


Figure 3.1: Microservice Architecture Explanation

3.2 System Architecture Diagram

The proposed wrist movement tracking system consists of four main functional components integrated within the overall upper limb rehabilitation platform. The system architecture demonstrates the interconnected nature of hardware sensors, data processing modules, machine learning classifiers, and user interfaces.

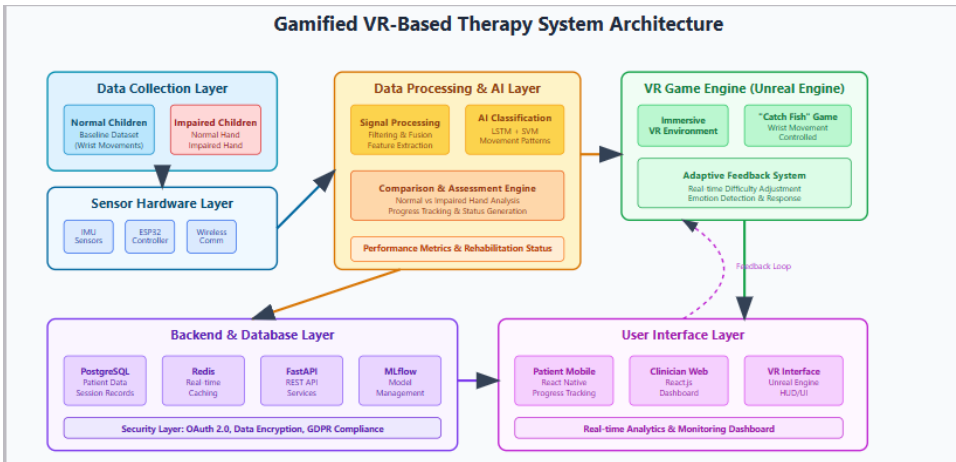


Figure 3.2: System Architecture Diagram

3.3 Software Solution

The software development life cycle (SDLC) is a systematic process that can produce high-quality, priced software in the shortest time possible. The goal of any SDLC is to create quality software that satisfies and meets all customer requirements and expectations. The SDLC has documented a comprehensive plan with stages, or phases that phases, each with its own process and deliverables. If you follow the SDLC, it will reduce project risk and costs, and will ultimately be faster than using different production methods.

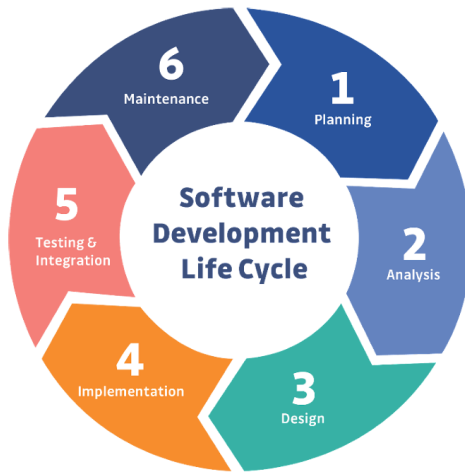


Figure 3.3: Phases of SDLC.

3.3.1 Requirement Gathering and Analysis

Clinical Requirements:

- Consultation with physiotherapy professionals specializing in pediatric hemiplegia rehabilitation.
- Analysis of existing wrist rehabilitation protocols and assessment criteria
- Understanding of specific movement patterns required for functional wrist mobility.
- Integration requirements with clinical workflow and documentation systems

Technical Requirements:

- Real-time motion tracking with < 100ms latency for responsive feedback

- Accuracy requirements for movement classification (>90% accuracy for basic wrist movements)
- Wireless communication range and battery life specifications
- VR hardware compatibility and performance requirements
- Data storage and security compliance for medical applications

User Requirements:

- Age-appropriate interface design for children with hemiplegia
- Accessibility considerations for users with motor impairments
- Engaging gamification elements to maintain therapy compliance
- Progress tracking and goal-setting capabilities

3.3.2 Feasibility Study

- **Technical Feasibility:**

The research team possesses expertise in embedded systems development, machine learning implementation, VR game development, and medical device integration. Available hardware platforms (ESP32, IMU sensors) and software frameworks (Unreal Engine, TensorFlow/PyTorch) provide a sufficient technical foundation for system implementation.

- **Financial Feasibility:**

Cost analysis indicates the wrist tracking module can be developed within reasonable budget constraints using commercially available sensors and development platforms. The modular design allows for incremental development and testing, reducing financial risk.

- **Clinical Feasibility:**

Collaboration with external supervisors from physiotherapy and rehabilitation medicine provides clinical validation and guidance throughout development. The

proposed system aligns with evidence-based rehabilitation practices and existing therapy protocols.

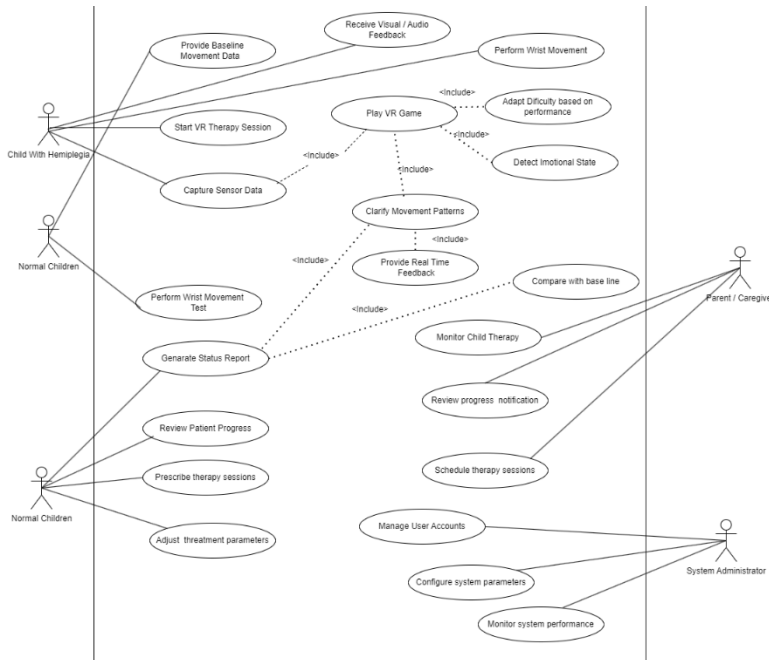
- **Operational Feasibility:**

The system is designed for both clinical and home-based use, with intuitive interfaces that minimize training requirements for therapists and caregivers. Cloud-based data management enables remote monitoring and therapy prescription.

3.3.3 Design Diagrams

3.3.3.1 Use Case Diagram`

The use case diagram illustrates primary actors (child patient, clinician, caregiver) and their interactions with the wrist tracking system, including therapy session management, progress monitoring, and system configuration.



3.3.3.2 Sequence Diagrams

Therapy Session Sequence:

1. System initialization and sensor calibration
2. Wrist movement data acquisition
3. Real-time motion classification
4. VR game interaction and feedback
5. Session completion and data storage

Clinical Dashboard Sequence:

1. Clinician authentication and patient selection
2. Progress data retrieval and analysis
3. Therapy prescription and goal setting
4. Report generation and export.

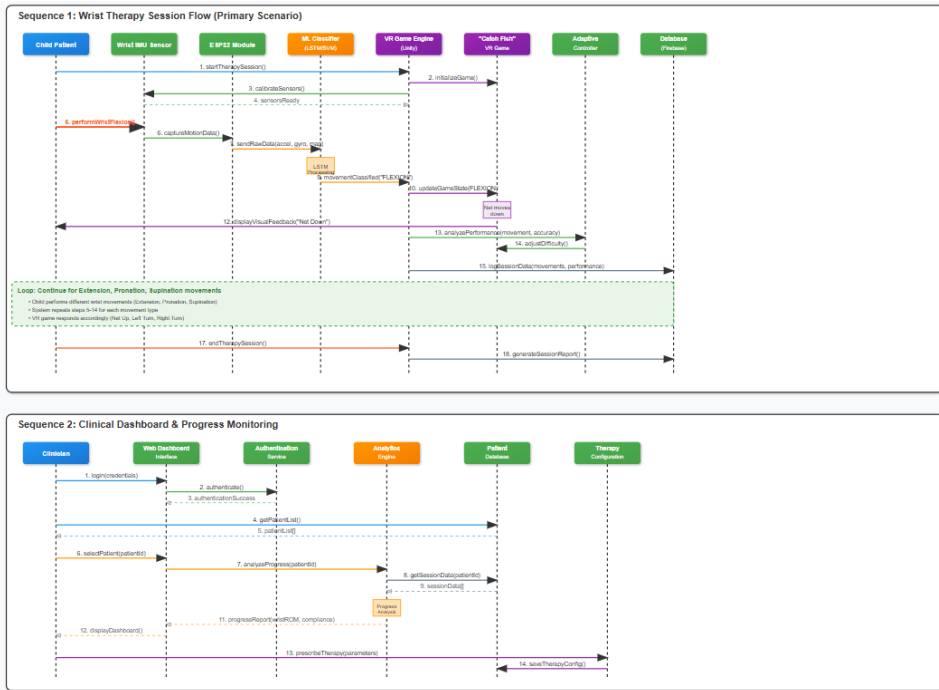


Figure 3.5: Sequence Diagram

3.3.3.3 System Design Architecture

Detailed system design showing component interactions, data flow, and interface specifications for the wrist tracking module within the broader rehabilitation platform.

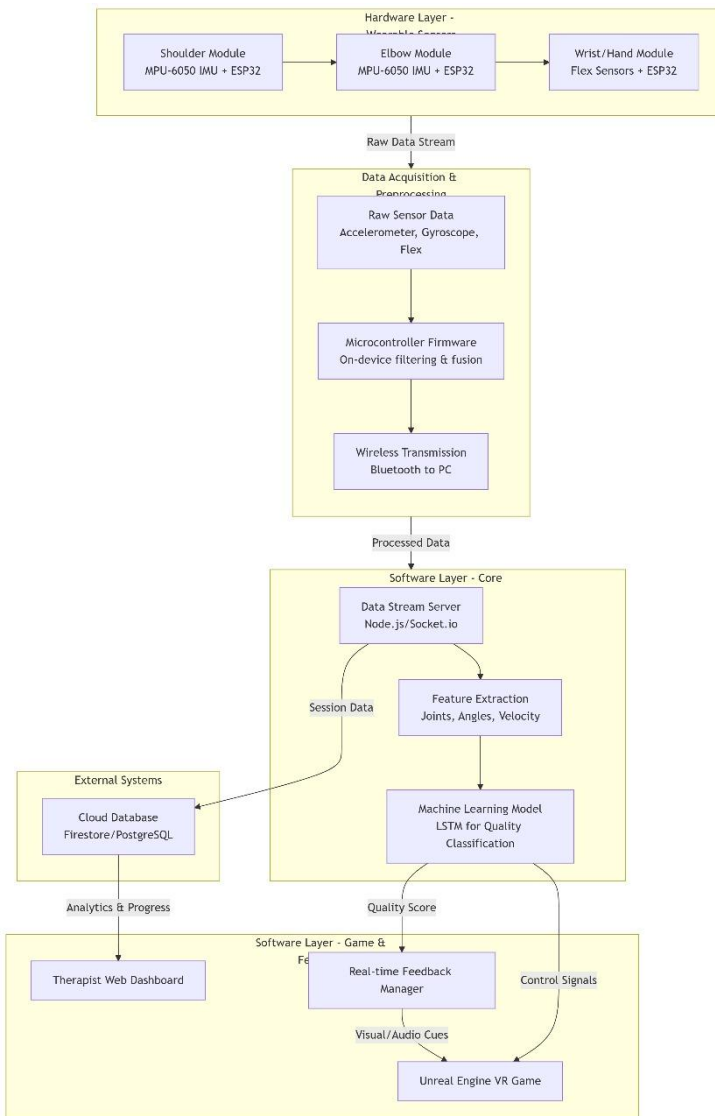


Figure 3.5: System Design Architecture

3.3.4 Dataset Requirements

Required datasets will be provided by Sirimavo Bandaranaike Specialized Children's Hospital with the field visits and the discussions we had with our external supervisors. To get the best outcome from the data set provided, it should be cleared up and pre-processed before using for the model training process.

Motion Data Collection:

- Wrist movement samples from the target population (children with hemiplegia)
- Normal movement patterns for comparison and calibration
- Diverse environmental conditions and sensor placements
- Longitudinal data for progress tracking validation

Data Preprocessing:

- Sensor calibration and alignment procedures
- Noise filtering and signal conditioning
- Feature extraction for movement classification
- Data augmentation techniques for robust model training

Clinical Validation Data:

- Standardized assessment scores (range of motion measurements).

- Therapist evaluations and progress notes.
- Functional outcome measures.
- User engagement and satisfaction metrics.

3.3.5 Implementation

- Select and integrate wearable sensors: IMU sensors (MPU-6050) and Flex sensors for capturing wrist motion.
- Program embedded systems using ESP32/Arduino IDE for real-time motion data acquisition and wireless communication.
- Develop ergonomic wearable module with 3D-printed enclosures, elastic straps, and lithium-ion batteries for portability and comfort.
- Apply signal processing techniques (Kalman filter, complementary filter) for noise reduction and accurate wrist motion tracking.
- Collect motion datasets from typically developing children and children with hemiplegia for training and calibration.
- Train machine learning models (LSTM using TensorFlow, SVM using scikit-learn) for the classification of wrist movements (flexion, extension, pronation, supination).
- Implement a VR therapy game (“catch fish”) in Unreal Engine 5.3+ using C++/Blueprint scripting.
- Integrate motion data with VR environment to provide real-time feedback and adaptive difficulty.
- Develop a clinician dashboard and backend using Node.js, MongoDB, and Firebase for session analytics, reporting, and progress tracking.
- Ensure modular microservice architecture for scalability and smooth integration with other rehabilitation components.

3.3.6 Testing Methodology

Technical Testing:

- Sensor accuracy validation using reference motion capture systems.

- Machine learning model performance evaluation (precision, recall, F1-score)
- System latency and real-time performance testing
- Wireless communication reliability and range testing

Clinical Testing:

- Pilot studies with children with hemiplegia under clinical supervision
- Comparative analysis with traditional therapy methods
- Therapist usability testing and workflow integration
- Patient engagement and compliance measurement

User Experience Testing:

- Age-appropriate interface testing with target demographic
- Accessibility testing for users with motor impairments.
- Gamification element effectiveness evaluation
- Long-term user retention and motivation assessment

3.3.7 Challenges and Mitigation Strategies

Technical Challenges:

- **Sensor Drift and Calibration:** Implement automatic calibration procedures and drift correction algorithms.
- **Movement Classification Accuracy:** Develop robust feature extraction and ensemble learning approaches.
- **Real-time Performance:** Optimize algorithms for embedded systems and implement efficient data processing pipelines.

Clinical Challenges:

- **User Compliance:** Design engaging, age-appropriate interfaces with adaptive difficulty progression.
- **Clinical Integration:** Work closely with healthcare professionals to ensure workflow compatibility.
- **Safety and Reliability:** Implement comprehensive error handling and failsafe mechanisms.

Implementation Challenges:

- **Hardware Miniaturization:** Balance sensor accuracy with wearable device size and comfort
- **Data Privacy and Security:** Implement robust encryption and comply with healthcare data regulations.
- **Scalability:** Design a modular architecture to support multiple simultaneous users

3.3.8 Expected Outcomes and Evaluation Metrics

Technical Outcomes:

- Wrist movement classification accuracy >90% for basic movements
- System latency <100ms for real-time feedback
- Wireless communication range >10 meters with reliable connectivity
- Battery life >4 hours continuous operation

Clinical Outcomes:

- Improved wrist range of motion in the target population
- Increased therapy compliance and engagement
- Objective progress tracking and documentation
- Enhanced clinical decision-making through data analytics

User Experience Outcomes:

- High user satisfaction scores (>4/5 rating)
- Sustained engagement over therapy duration
- Successful integration into existing therapy routines
- Positive feedback from both patients and clinicians

4. PROJECT REQUIREMENTS

4.1 Functional Requirements

- **Successfully assess and track the child's wrist movement skills and rehabilitation progress.**
 - Real-time capture and analysis of wrist flexion, extension, pronation, and supination movements
 - Continuous monitoring of range of motion improvements over therapy sessions
 - Automatic detection and classification of movement patterns using ML algorithms
 - Progress tracking through standardized clinical assessment metrics (QUEST, Melbourne Assessment).
- **The progress of the child should be analyzed and can be viewed by the Parent/Guardian/Therapist.**
 - Comprehensive dashboard displaying therapy session analytics and movement improvement trends
 - Visual progress reports with charts and graphs showing range of motion changes
 - Historical data comparison to track long-term rehabilitation outcomes
 - Mobile app access for parents/guardians to monitor the child's progress remotely

- **Full Control of the therapy process for the therapist, giving the ability to mention specific tasks.**
 - Therapist portal for prescribing customized wrist rehabilitation exercises
 - Task configuration interface allowing selection of specific movements and difficulty levels
 - Session duration and frequency control based on individual patient needs
 - Real-time therapy session monitoring and intervention capabilities

- **Use ML/AI for analyzing movement patterns and therapy effectiveness.**
 - Machine learning models (LSTM, SVM) for accurate movement classification
 - Deep learning algorithms for movement quality assessment and correction
 - Predictive analytics for therapy outcome forecasting
 - Pattern recognition for identifying compensatory movement strategies

4.2 Non-Functional Requirements

- Attractiveness on the Gamified Interface.
- Easily usable by the children.
- Generate high-accuracy analytics reports.
- Handling the privacy of a large amount of data.

- Availability of the therapy sessions.

4.3 Hardware Requirements

4.3.1 Wearable Sensor Components

- IMU Sensors (MPU-9250 or BNO055): 4 units for shoulder, elbow, wrist, and finger tracking
- Flex Sensors: 5 units for individual finger movement detection.
- ESP32 Development Boards: 4 units for real-time data processing and wireless communication
- Custom PCB Boards: For sensor integration and miniaturization
- Lithium-ion Batteries (3.7V, 1000mAh): 4 units for portable operation
- 3D Printed Enclosures: Lightweight, ergonomic housing for wearable modules.
- Elastic Straps and Velcro: For comfortable and adjustable sensor mounting.

4.3.2 Enhanced VR Hardware Requirements

- **High-end VR Headset (Meta Quest 3, Valve Index, or Pico 4):** For optimal visual fidelity and tracking
- **Dedicated VR-Ready PC:** NVIDIA RTX 4070/AMD RX 7700 XT or better for Unreal Engine 5 performance
- **High-speed wireless connection:** For streaming VR content and sensor data simultaneously

4.4 Software Requirements

4.4.1 Development Platforms

- Unreal Engine 5.3+: Primary VR game development environment with advanced rendering capabilities
- Visual Studio 2022: C++ development environment for Unreal Engine plugins
- Arduino IDE: For embedded system programming
- Python 3.9+: For machine learning model development
- Visual Studio Code: Integrated development environment
- Git: Version control system

4.4.2 Machine Learning Frameworks

- TensorFlow 2.x: For LSTM model development and training
- scikit-learn: For SVM implementation and data preprocessing.
- NumPy & Pandas: For data manipulation and analysis
- Matplotlib & Seaborn: For data visualization and analysis
- Unreal Engine Python Integration: For connecting ML models with game engine

4.4.3 VR and Game Development Tools

- Unreal Engine VR Template: Optimized VR project foundation
- Blueprint Visual Scripting System: For rapid therapy game development
- MetaSounds: For procedural audio and adaptive sound design
- Niagara Particle Systems: For advanced visual effects and feedback
- Unreal Engine Marketplace Assets: For high-quality 3D models and environments
- Blender: For custom 3D asset creation and animation

- Adobe Creative Suite: For UI/UX design and visual assets
- Quixel Megascans: For photorealistic textures and 3D assets

4.4.4 Database and Backend

- Firebase: For real-time data synchronization and user authentication
- Node.js: Backend server for clinician dashboard
- MongoDB: Database for storing patient data and therapy sessions
- Chart.js: For progress visualization in the clinician dashboard

4.5 Personnel Requirements

- Dr Buddika Senavirathne,
Head of Physiotherapy (Pediatric) and Rehabilitation,
Sirimavo Bandaranaike Specialized Children's Hospital,
Kandy, Sri Lanka.

5. PROJECT BREAKDOWN

5.1 Gantt Chart

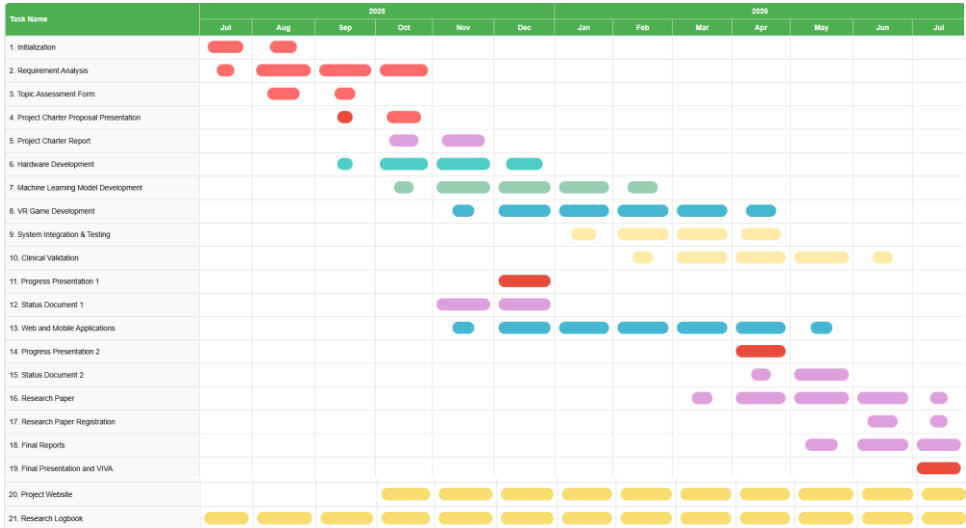
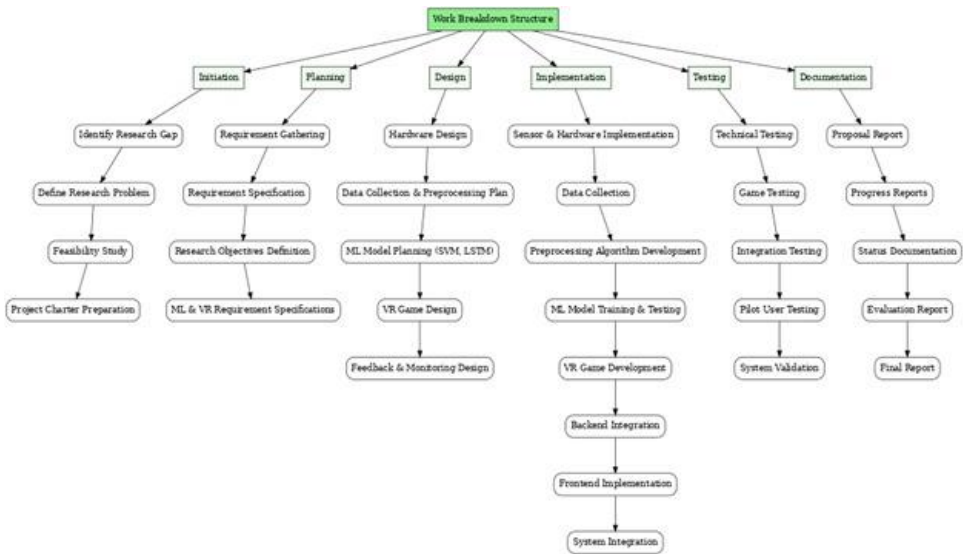


Figure 6.1 : Gantt Chart

5.2 Work Breakdown Structure



6. DESCRIPTIONS OF PERSONAL AND FACILITIES

➤ **Facilitators: -**

- Mr. Didula Thanaweera Arachchi - Sri Lanka Institute of Information Technology
- Mr. Eishan Dinuka - Sri Lanka Institute of Information Technology
- Dr. Buddika Senavirathne - Sirimavo Bandaranaike Specialized Children's Hospital, Kandy, Sri Lanka.

➤ **Facilities: -**

- Sirimavo Bandaranaike Specialized Children's Hospital, Kandy, Sri Lanka.

7. COMMERCIALIZATION

The primary target users of this system are pediatric rehabilitation centers, clinics, and hospitals that provide therapy to children with hemiplegia or other upper-limb motor impairments. Specifically, the system is low-cost, portable and fun for children to use making it applicable in both clinical and home-based rehabilitation settings.

Additional potential markets and user groups

- **Home-based caregivers and parents**

Parents looking for convenient, safe, and motivating rehabilitation solutions for children at home.

- **Pediatric physiotherapists and pediatric occupational therapists.**

These users may benefit from the objective monitoring, tracking progress of children, and ability to manage/monitor patients remotely.

- **Educational institutions and therapy centers.**

Schools or centers that provide therapeutic programs for children with motor disabilities.

- **Research institutes and universities.**

Institutions that are studying pediatric rehabilitation, human-computer interaction, and/or gamified therapy methods.

- **Tele-rehabilitation service providers.**

Businesses or start-ups offering therapy services remotely, especially in areas where a pediatric rehabilitation specialist may not be accessible.

Hardware components of the system (ESP32, flex sensors, and VR headset) are low-cost and easily procured, which supports its commercial marketability in both high-resource and low-resource areas. The software solution has architecture that makes scaling possible - thus increasing service delivery of a solution for children needing rehabilitation for motor impairments. The system uses a modular structure that will allow it to generate subscription-based software as a service, sell the devices and/or integrate with telehealth platforms, generating different revenue streams, but ultimately increasing the ease of accessing pediatric rehabilitation solutions.

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APPENDICES

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