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Development of a Wireless Sensor to Monitor Head Kinematics Under Impact Loading

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Abstract: Traumatic Brain Injuries (TBIs), particularly mild traumatic brain injuries (mTBIs), represent a critical concern in contact sports, industrial applications, and military environments. Early detection and continuous real- time monitoring of head impacts are essential for reducing the risk of long-term neurological damage. This research focuses on designing, developing, and validating a compact wireless sensor system that captures both linear and angular head motion parameters with high precision. The system integrates the H3LIS331DL high-g triaxial accelerometer and the MPU6050 3-axis gyroscope with an ESP32 microcontroller to facilitate data acquisition and wireless transmission. Using the MQTT protocol over Wi-Fi, impact data are transmitted in real time to cloud-based platforms (ThingsBoard) and a local WebSocket dashboard, supporting both online and offline analysis. The system emphasizes low power consumption via event- driven data logging, which activates only when impacts exceed a configurable threshold. Extensive testing under controlled laboratory conditions, including pendulum-based impact validation and comparison with reference devices, demonstrated measurement accuracy within 5% error margins. Real-time visualization ensures intuitive user interaction and prompt medical or coaching interventions. This research provides a robust, energy-efficient, and low- cost solution suitable for wide-scale implementation in sports, industrial safety, and military applications, contributing significantly to injury prevention and impact biomechanics research.

Key Words: Wireless Sensor, Head Impact Monitoring, Traumatic, ESP32, IMU, Real-Time Data Visualization, Web-socket.

Introduction

Traumatic Brain Injuries (TBIs) are a leading cause of disability and death worldwide, particularly in contact sports and high-risk occupations. According to the Centers for Disease Control and Prevention (CDC), millions of TBIs are reported annually, with sports-related concussions comprising a significant portion. The subtle and often delayed presentation of mild TBIs makes their detection challenging, creating an urgent need for reliable real-time monitoring tools.

Head Impact Monitoring a Necessity:

Accurate detection of head impact kinematics helps prevent secondary injuries by providing timely data for medical assessment. Traditional post-event diagnosis methods rely on subjective reporting and delayed imaging techniques. However, wearable sensor systems enable objective, continuous, and event-driven measurement of linear accelerations and angular velocities that are biomechanically linked to injury risk.

1.1 Role of Wireless Solutions:

Conventional wired sensors are impractical in dynamic environments due to movement restrictions and risk of wire damage. Wireless solutions overcome these limitations by enabling real-time, uninterrupted data transfer via technologies such as Wi-Fi and MQTT protocol [1]-[6]. This allows coaches, clinicians, and researchers to monitor and analyses impact events remotely, improving decision-making and injury management.

I. LITERATURE REVIEW

Extensive studies highlight the challenge of measuring accurate head impact data in real-world settings due to sensor drift, noise, and environmental factors. Studies by [7] and [8] emphasize the critical thresholds for concussive impacts, typically ranging from 10g to 98g linear acceleration. Several studies [9]–[11] have used linear impactor to replicate accidental loading conditions, with the primary objective of measuring head kinematics during such events. These investigations predominantly utilized wired sensor systems for data acquisition. Wearable sensors often used to measure the kinematics during the impact events [12]

Existing wearable systems often suffer from:

- Lack of real-time dashboards for immediate feedback.
- Continuous data transmission leading to battery drain.
- Incomplete sensor fusion methods.
- Fragmented system integration without seamless data analysis pipelines.

This research addresses these limitations by integrating low-power sensors and an ESP32 microcontroller into a compact system capable of reliable real-time monitoring with event-driven data transmission.

II. METHODOLOGY

3.1 System Design Overview:

The wireless sensor system is structured into six key functional components: 1. Sensor Module: H3LIS331DL accelerometer for high- g linear motion and MPU6050 gyroscope for angular velocity measurement. 2. Microcontroller Integration: ESP32 microcontroller using I2C for synchronized data acquisition. 3. Impact Detection Logic: Event-triggered data logging when acceleration exceeds 10g. 4. Wireless Data Transmission: MQTT and WebSocket for cloud and local dashboards. 5. Power Management: 3.7V Li-Po battery with safe charging. 6. Data Visualization: Real-time display of acceleration and angular velocity data.

3.2 Hardware Development:

The head impact monitoring system was designed as a compact, wireless, and modular device capable of measuring both linear and angular head kinematics. Its architecture prioritizes portability, durability, and suitability for high-impact applications such as sports and biomechanical testing.

Hardware Enclosure and Integration:

A lightweight custom enclosure was developed to protect sensitive components including the ESP32 microcontroller, MPU6050 IMU, H3LIS331DL accelerometer, Li-Po battery, and supporting circuits while maintaining user comfort. The design focused on:

1. Secure component housing with slots for PCBs and sensors.
2. Shock protection using a rigid flanged casing that absorbs incidental impacts.
3. User accessibility via a detachable top plate for calibration and maintenance.
4. Thermal management with ventilation slots to dissipate heat.
5. Compactness and portability, keeping the total mass below 450 g for head-mounted use.
6. Ease of prototyping, with all parts optimized for 3D printing.

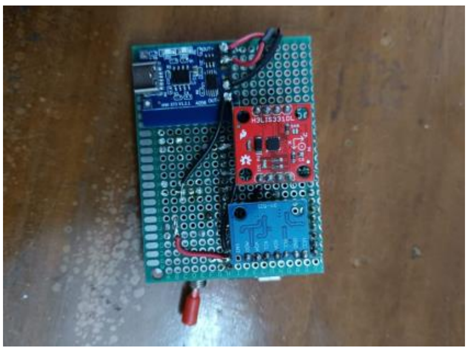

Fig -3.2.1: Sensor setup(z-axis placed opposite g)

Fig -3.2.2: Sensor setup(z-axis placed along g)

Enclosure Design

The enclosure consists of three parts:

- Main casing: Designed as a rectangular box-like shell with ventilation slots and a central pillar for PCB support.
    - *Mass: 326.7 g*
    - *Volume*: 41,619 mm³
    - *Surface Area*: 41,774 mm²

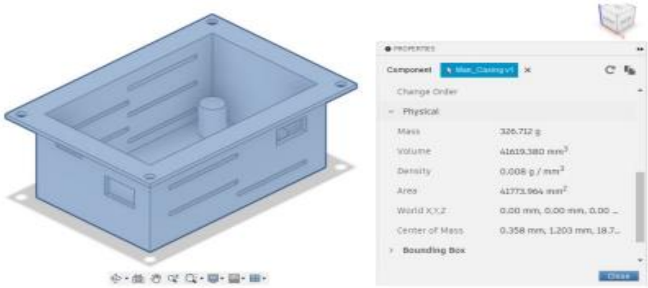

Fig -3.2.3: Structure of the casing

- Top plate: Acts as a removable lid with alignment holes and a central cut-out for LED visibility or external port access.
    - *Mass*: 119.6 g
    - *Volume*: 15,235 mm³
    - *Surface Area*: 16,164 mm²

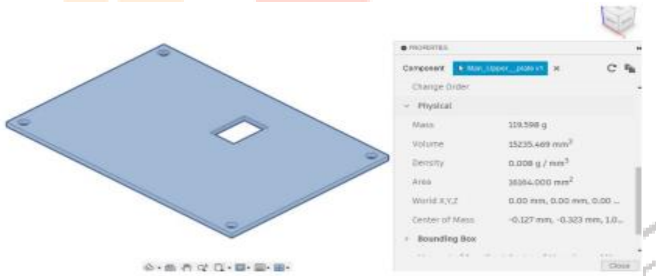

Fig -3.2.4: Structure of the plate of casing

- Mounting screws: Standard M3 machine screws selected for tight fit and vibration resistance. Each screw has:
    - *Mass*: 1.42 g
    - *Volume*: 182 mm³

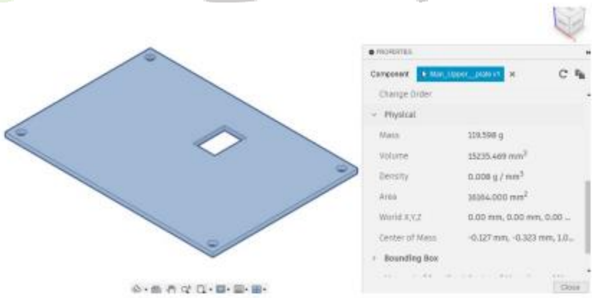

Fig -3.2.5: Structure of the screw of casing

This modular three-part enclosure balances structural integrity, lightweight design, and user accessibility. With a combined weight of approximately 447 g, it is suitable for helmet integration without affecting comfort. Its 3D-printable geometry supports rapid prototyping and small-batch production, making it practical for both research validation and future field deployment.

Fig -3.2.6: Sensor setup with casing

3.3 Firmware and Software Development

The firmware and software form the core of the wireless head impact sensor, enabling accurate acquisition, processing, and transmission of motion data. The ESP32 microcontroller serves as the central platform, offering dual-core processing, integrated Wi-Fi, and low-power operation suitable for wearable devices.

Embedded Firmware:

The firmware is designed to capture both linear acceleration and angular velocity from the onboard MPU6050 (low-g accelerometer and gyroscope) and H3LIS331DL (high-g accelerometer). Data is acquired via the I^2C protocol, calibrated for sensor offsets, and sampled at 500–800 Hz to ensure high temporal resolution. Filtering techniques, including Kalman and Moving Average filters, are applied to reduce noise and enhance signal reliability.The ESP32's multi-core architecture allows one core to handle sensor acquisition and preprocessing, while the other manages wireless communication. Power-efficient features such as deep sleep modes and interrupt-based wake-ups extend battery life, making the system practical for field use.

Software Architecture:

The software follows a modular design, enabling adaptability to different sensor configurations and communication protocols. It can have sensor interfacing and calibration, real-time impact detection algorithms, signal conditioning and noise reduction and data formatting and wireless transmission.

Data is transmitted in real time via Wi-Fi using MQTT, and visualization is supported through cloud dashboards (e.g., ThingsBoard) or local web interfaces. These dashboards provide live plots, alerts, and easy interpretation of head impact events, supporting applications in sports, clinical monitoring, and biomechanical studies.

3.4 Experimental Setup:

Controlled impact experiments employed pendulum tests, mobile accelerometer for cross- validation, and YMC piezotronics as a reference sensor to ensure measurement accuracy.

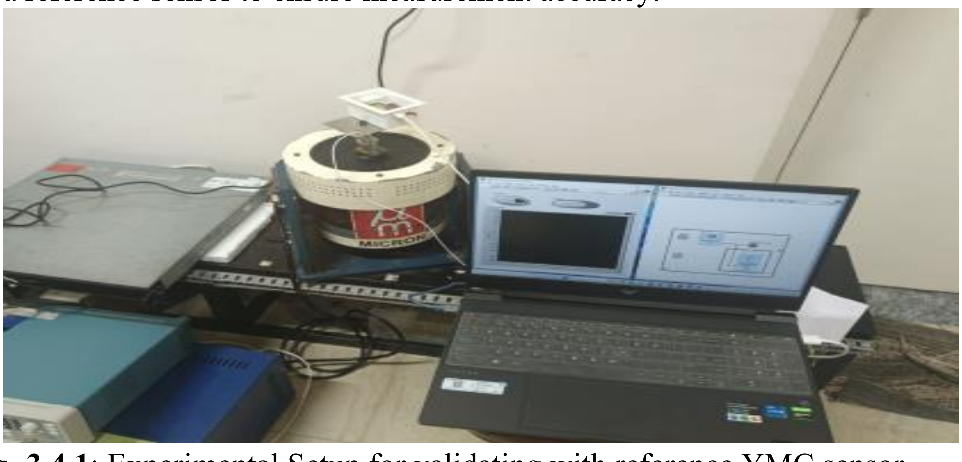

Fig -3.4.1: Experimental Setup for validating with reference YMC sensor

Fig -3.4.2: Experimental Setup for validating with plumbob setup

III. RESULTS AND DISCUSSIONS

4.1 Stationary Test Results (Pre-Calibration):

Prior to applying calibration routines, the sensors were evaluated under stationary conditions to analyze their inherent raw output behavior. The H3LIS331DL high-g accelerometer and MPU6050 gyroscope were placed on a stable surface, and their signals were monitored without external motion or disturbances.

Observations: Accelerometer (H3LIS331DL): The X and Y axes recorded small offsets around 0.02 g, while the Z-axis deviated from the expected −1 g due to gravity. A sudden dip in signal was noted at ~150 ms.

Gyroscope (MPU6050): Despite no movement, angular velocity fluctuated between −0.02 to 0.08 °/s, revealing zero-rate bias and noise.

Interpretation: These offsets are a manifestation of sensor bias, drift, and noise, which are common in MEMS sensors.

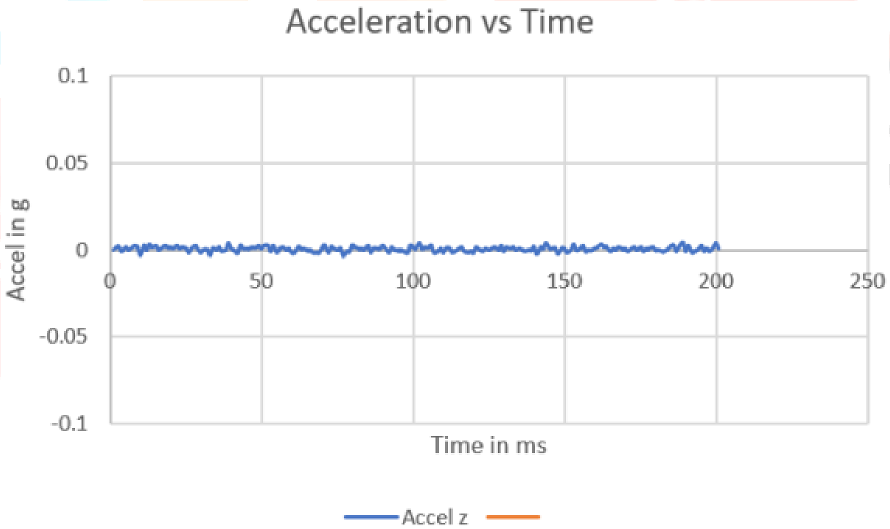

Fig -4.1: Acceleration vs Tims graph(H3LISS31DL)

4.2 Calibration Results:

Calibration was performed to eliminate static offsets and improve precision.

Accelerometer (H3LIS331DL): After applying offset correction, the X and Y axes stabilized near 0 g, while the Z-axis consistently measured around −1 g, as expected due to gravity.

Gyroscope (MPU6050): Zero-rate drift was significantly reduced, with all axes reporting close-to-zero angular velocities during stationary tests.

This confirmed the success of calibration in reducing bias and enabling reliable measurements.

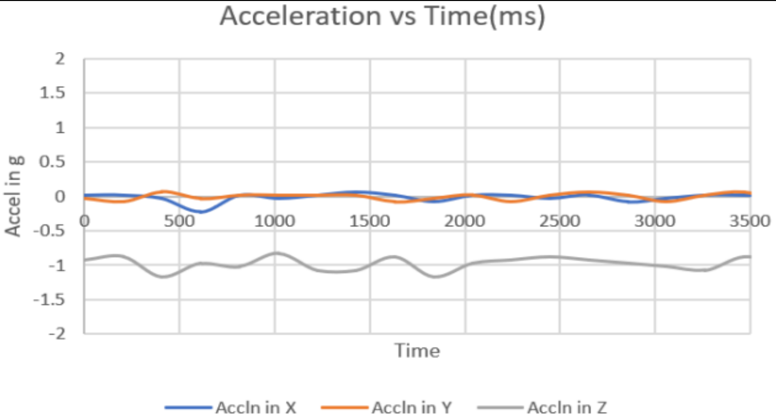

Fig -4.2: Acceleration (g) vs Time (ms) graph after calibration

4.3 Dynamic Testing:

Dynamic evaluation involved intentional impacts.

Accelerometer: The Z-axis recorded a sharp negative peak (~−6 g) during impact, validating the ability to capture high-g events.

Gyroscope: Angular velocity spiked above 150 °/s, confirming accurate detection of rotational motion.

Calibration enabled clear distinction between stationary noise and true dynamic events.

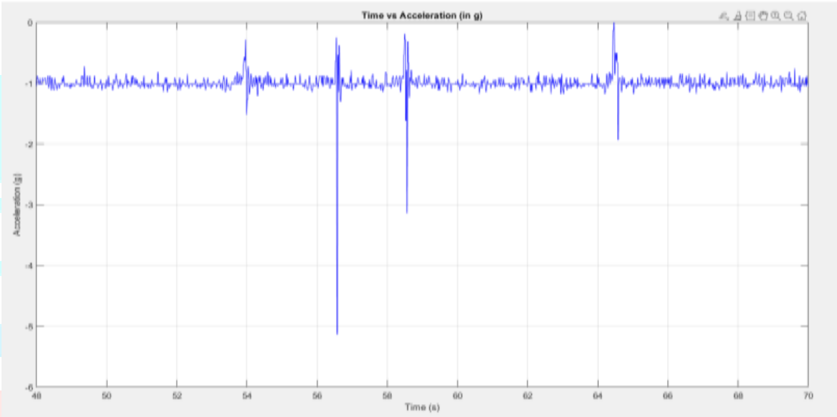

Fig -4.3: Acceleration vs Time(dynamic)

4.4 Wireless Data & Dashboards:

Data were transmitted to Things Board and a custom web dashboard with minimal latency. Both visualized real-time acceleration/gyroscope data effectively. The custom dashboard offered faster updates, but lacked logging and mobile support.

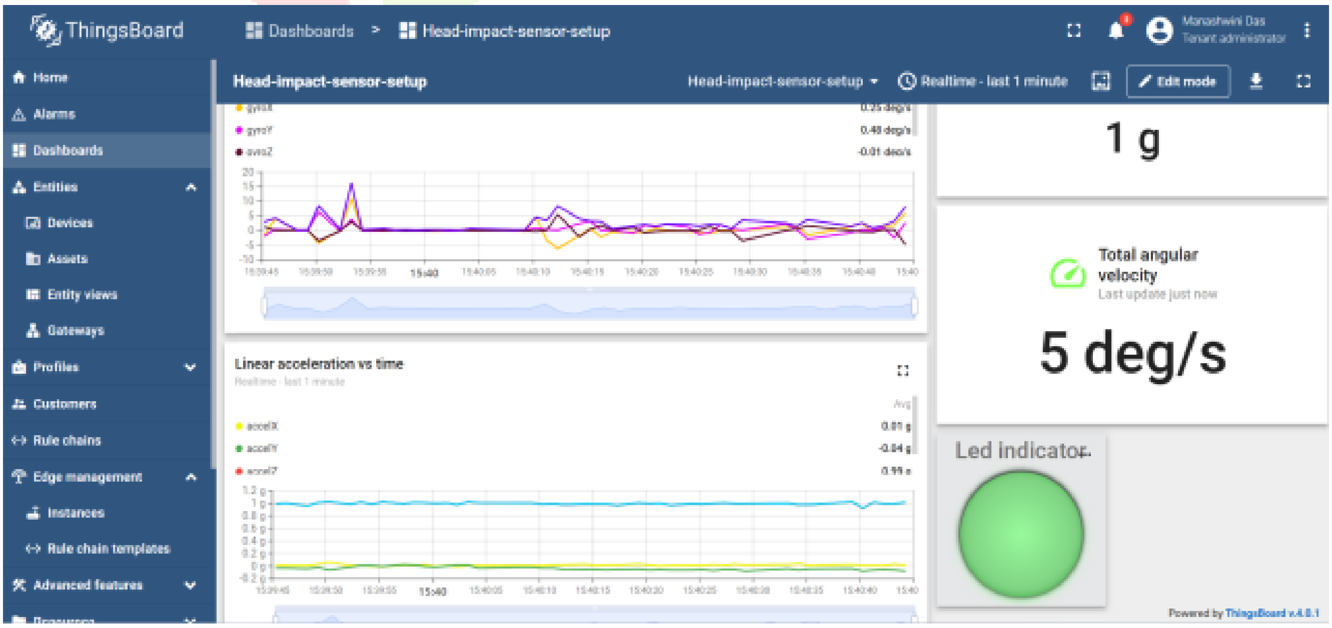

Fig -4.4.1: Thingsboard-dashboard

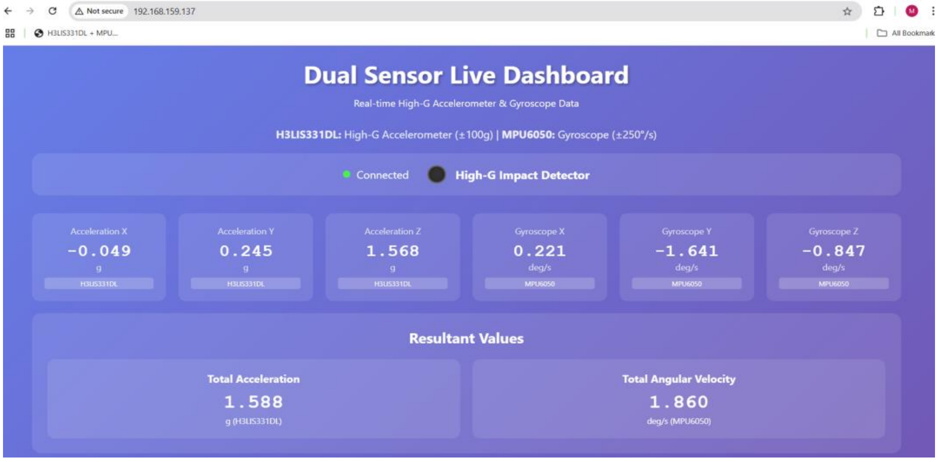

Fig -4.4.2: Webpage showing real time data

4.5 Validation with Reference Devices:

To ensure measurement reliability, the developed sensor was compared with:

Mobile Accelerometer: Comparable results under static (~1 g on Z-axis) and dynamic (~2 g) conditions.

YMC Piezotronics Sensor: Correlation of ~80.6%, confirming reliability despite lower sampling rate of developed sensor.

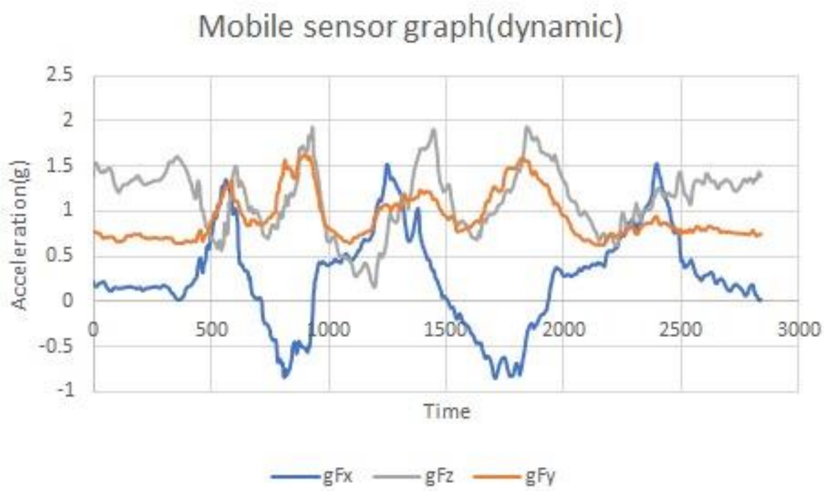

Fig -4.5.1: The dynamic acceleration data from the mobile accelerometer is shown, with the X-axis representing time in milliseconds (ms) and the Y-axis representing linear acceleration in g.

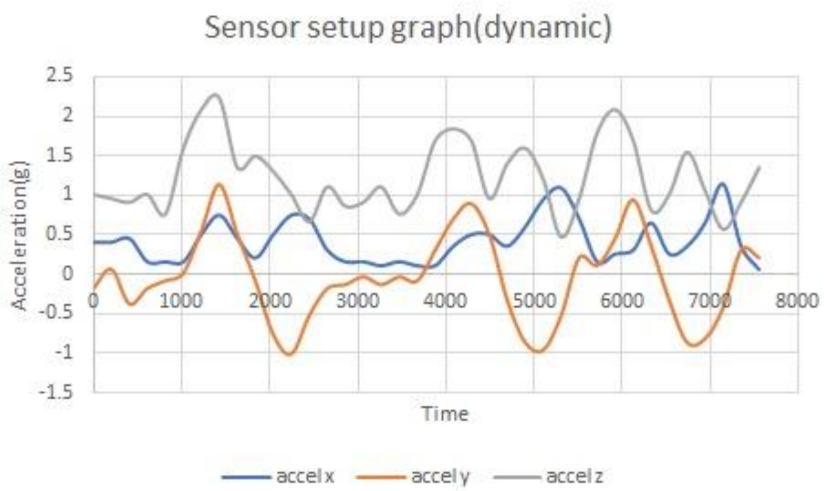

Fig -4.5.2: The acceleration data of the dynamic sensor setup is shown, with the X-axis representing time in milliseconds (ms) and the Y-axis representing linear acceleration in g

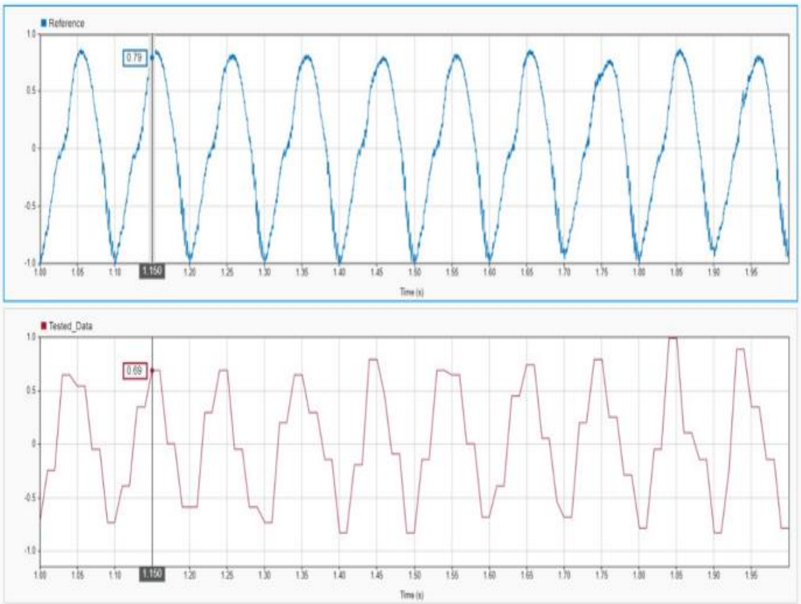

Fig -4.5.3: Graph obtained from testing with YMC piezotronics sensor as reference

4.6 Power Consumption Analysis:

Energy demand was tested using a 3.7V, 2000 mAh Li-Po battery:

- Idle: ~52 mA
- Acquisition: ~71 mA
- Transmission: ~138 mA

The system can run ~14–15 hours in continuous mode. Energy optimization (duty cycling, BLE, or harvesting) can extend operational life for wearable applications.

Discussion: The highest energy demand was during wireless transmission, accounting for nearly 2.6× more power than idle state. At ~138 mA draw, the system can continuously operate for 14–15 hours on the tested Li-Po battery. This indicates suitability for short-term sports sessions or controlled experiments, but longer deployments would require energy optimization strategies such as:

- Duty cycling and adaptive sampling
- Low-power transmission modes (MQTT, BLE)
- Energy harvesting add-ons (solar or kinetic charging)

IV. CONCLUSIONS

The research developed a compact wireless head-impact monitoring system using the H3LIS331DL accelerometer, MPU6050 IMU, and ESP32 microcontroller. The system successfully captured accurate acceleration and angular velocity data, with calibration reducing noise and bias. Event-triggered acquisition improved power efficiency, while wireless transmission enabled real-time visualization through both cloud and local dashboards. Validation against reference sensors confirmed reliability, making the system suitable for sports safety, injury detection, and wearable motion monitoring applications.

The limitation of the developed system is that the sensor was validated for low-magnitude impact events

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