

Design and Development of an Automated Gymnastics Movement Evaluation Device

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Abstract— The assessment of rhythmic gymnastics need precision, balance, and harmonious body coordination. It is often carried out with visual observation. This research aims to develop a sensor-based assessment system to process, classify, and score measurement data automatically. An ADXL335 accelerometer sensor and an HMC5883L magnetometer sensor are integrated with an ESP32-C3 mini transmitter to acquire three-axis acceleration and heading data in real time. The receiver sends data to a PC application that performs downsampling with average pooling to reduce signal density, min-max normalisation to harmonise scale across axes, and compares the processed test sequence against reference data. Deviations are quantified through per-parameter error computation, which is converted to accuracy and generate an overall performance score by combined using predefined weights that is displayed on an LCD/P10 panel. Experimental trials on SKJ 2012 warm-up movements show that the proposed method can classify sensor data and generate scoring outputs. The findings indicate that sequences closely matching the reference pattern consistently yield high scores about 80–85, while deliberately incorrect movement produce much lower scores, around. This research provides an objective, repeatable, and real-time scoring mechanism that approach for transforming sensor measurements into interpretable assessment results.

Index Terms— ADXL335 Accelerometer; HMC5883L Magnetometer; Average Pooling; Min-Max Normalisation; Rhythmic Gymnastics Performance Evaluation

I. INTRODUCTION

Rhythmic gymnastics combines repeated body movement, timing, balance, and coordination. The objective of gymnastics is to enhance health and physical fitness [1] [2]. The intensity of gymnastic movements varies according to the rhythm of the selected music [3]. In order to determine the quality of performance and competence of participants in performing movements in accordance with the movement references of each gymnastics routine, the evaluation process in sports activities must be considered. Currently, rhythmic gymnastics students

are predominantly assessed manually that rely on visual observation. Nevertheless, this approach is tends to inconsistency and bias due to factors such as assessor fatigue, environmental conditions and time constraints that are difficult to avoid [5]. Wearable inertial sensors provide a practical route to reduce this subjectivity because they can record body motion directly during training [4]. Automatic scoring has also been explored in other sports contexts, such as electronic scoring for taekwondo, and statistical approaches have been discussed for improving fairness in gymnastics judging [6]. Research undertaken hitherto has demonstrated that the implementation of accelerometer and magnetometer sensors can be utilised to facilitate the monitoring of rhythmic gymnastics activities in conjunction with an Android application [7]. However, the present research has not been equipped with an automatic assessment feature that can directly generate a final score for gymnastics activities. Moreover, concomitant research employing the HMC5883L magnetometer sensor for the development of shooting practice and research on tools for monitoring sit-ups with accelerometer and gyroscope sensors demonstrates that the application of sensor technology can enhance the accuracy of movement phase determination [8] [9].

Accordingly, this research developed an automatic gymnastics movement assessment system as a pioneering solution that minimizes subjectivity and inconsistency in the assessment process [10]. The system comprises an ESP32-C3 Mini as a transmitter and a Wemos D1 Mini ESP32 as a receiver, operating in an integrated manner. The transmitter module is employed to collect data from the ADXL335 accelerometer and HMC5883L magnetometer sensors, thereby enabling the real-time recording of SKJ 2012 [11] [12] [13]. Meanwhile, the receiver module, comprising the power supply and LCD components, is tasked with receiving data, processing the data sent to the application, and sending the score to the display as a form of data visualisation.

II. METHOD

In this research, an automatic gymnastics movement assessment tool was designed using the downsampling method with average pooling and min-max normalisation. Integrating key components such as the ADXL335 accelerometer sensor, HMC5883L magnetometer sensor, ESP32 C3-Mini, and Wemos D1 Mini ESP32 using client-server communication [14] [15].

A. System Design

The device's design requires the utilisation of a block diagram to facilitate comprehension of its operational workflow. The design of this device consist of three modules: the transmitter module, the receiver module, and the display panel module. As illustrated in Figure 1a, the transmitter module facilitates the transmission of sensor data to the receiver module, a process that necessitates the utilisation of several components, including the ESP32-C3 mini, a magnetometer sensor, an accelerometer sensor, a 18650 Li-Ion battery, an on-off switch, an LED, and a step-down voltage regulator. As illustrated in Figure 1b, the receiver module is responsible for the processing of data and the transmission of values to the display panel module, which subsequently displays the values visually. The components required for the construction of the device are as follows: an on-off switch, a DF player mini, a 12V SMPS, a Wemos D1 mini ESP32, a 20x4 LCD, a push button, an LED, an EEPROM, a PAM 8610, a step-down voltage regulator, an HC-05 Bluetooth module, and a PC. Meanwhile, the components in Figure 1c require a 5V SMPS, HC-05 Bluetooth module, Arduino Nano, and P10 display panel.

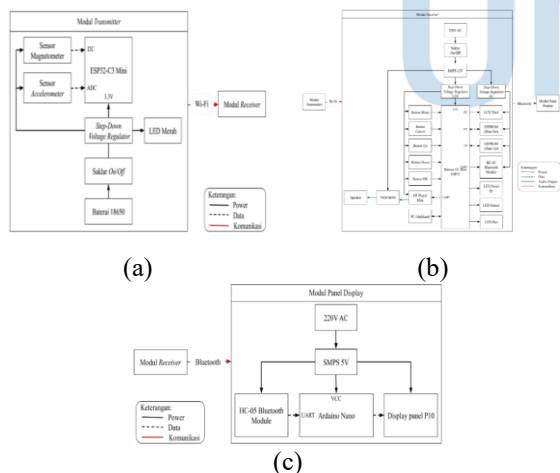


Figure 1. Block Diagram of the Module System (a) Transmitter and (b) Receiver (c) Display Modul panel

In the process of designing an automatic gymnastics movement assessment tool, the flowchart or flow diagram illustrating the overall working concept can be found in Figure 2. The preliminary stage in the system

design process is to initiate the system, which involves configuring the hardware and software to enable connection. This encompasses the configuration of the transmitter and receiver modules, the initialisation of the microcontroller, the initialisation of the accelerometer and magnetometer sensors for data collection, and the activation of the LCD and button inputs. Subsequent to the establishment of a connection, the user is able to select the type of rhythmic gymnastics to be used. The sensors will immediately record body orientation and movement data in real time, then transmit it to the server via a Wi-Fi connection and forward it to the PC/laptop application [16]. The test data will then be compared with the master data from the application. The participant's performance score is calculated based on various predetermined parameters. This score will then be transmitted back to the server via Bluetooth connection and forwarded to the display panel module. The retesting process can be repeated by executing the same procedure once more.

The complete workflow is shown in Figure 2. After the system is initialized, the user selects the gymnastics routine to be evaluated. The transmitter then records acceleration and orientation data while the participant performs the movement. The receiver sends this data to the PC application, where the test sequence is processed and compared with the master sequence. The calculated score is returned to the receiver and then sent to the P10 display.

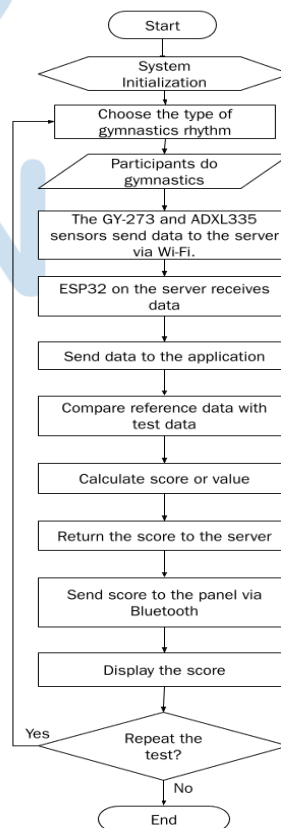


Figure 2. System Flowchart

B. 3D Design

The 3D design consists of three constituent parts: a transmitter module measuring 10 x 7.5 x 3.5 cm, a receiver module measuring 23.5 x 19.5 x 10 cm, and a display panel module measuring 69 x 37 x 5 cm. The transmitter module is composed of 1 mm-thick plastic, with a relatively diminutive size. It is equipped with an on/off switch and LED indicator to signal that the module is active. The receiver module has been equipped with ventilation on the side and top to prevent overheating, and is equipped with a 20 x 4 LCD, 5 buttons for menu navigation and system settings, 3 LEDs for indicators, and a front panel with an on/off switch. The display panel module is equipped with four panels, each with a black casing to protect the components.

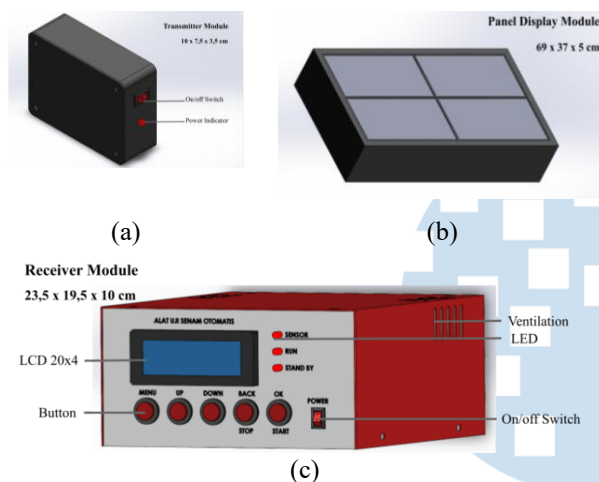


Figure 3. 3D Design of Modules (a) Transmitter, (b) Display Panel, (c) Receiver

C. Specifications and Features

The specifications and features required for an automatic gymnastics assessment tool consist of a system with accelerometer and magnetometer sensors, wireless sensor data via Wi-Fi protocol with IP address configuration, a receiver module with settings and selection of gymnastics accompaniment songs, movement assessment results, a transmitter module with compact and lightweight LED indicators, and a 120,000-byte sensor data storage system.

D. Software Design

The design of software is initiated with the acquisition of sensor data on the transmitter module, where the ADXL335 accelerometer sensor is converted from analogue to digital signals via a 12-bit ADC (with a sampling rate of 25 Hz), while the HMC5883L magnetometer sensor transmits data in digital format via the I2C communication protocol [17] [18]. The data are sent to the receiver module is facilitated by means of Wi-Fi UDP communication. It is evident that the measurements obtained from the two types of sensors result in the generation of four parameters,

namely the X, Y, Z axes, and direction [19]. The subsequent stage of the process is the sensor data processing stage, which includes downsampling using the average pooling method and min-max normalisation. The evaluation of test data is achieved through a comparison with master data, with the error value per parameter being calculated using equations 1 and 2. Subsequently, the accuracy is calculated based on equation 3, then multiplied by the weighting of each parameter according to equation 4 to obtain a final score, which is then displayed on the display panel.

$$Total\ error_i = \sum |reference\ value_i - measured\ value_i| \quad (1)$$

$$Relative\ error_i = \frac{Total\ Error_i}{\sum |Total\ Reference\ error_i|} \times 100\% \quad (2)$$

$$Accuracy_i = 100 - Relative\ error_i \quad (3)$$

$$Score = \sum Evaluation \times Accuracy_i \quad (4)$$

E. Hardware Design

The hardware assembly is begun with the selection and testing of elements that are deemed essential to the functionality of the device. These components encompass the power supply, the display panel, the microcontroller, the ADXL335 accelerometer sensor, and the HMC5883L magnetometer sensor. Subsequently, the direction and placement of the transmitter module in the participant's back pocket are determined in order to obtain data with sensors that are adjusted according to the direction of the body. The subsequent stage involves the assembly and integration of components such as PCB components, cable connections, and displays for the gymnastics movement assessment device, as well as testing the hardware system, which includes sensor response, checking communication between modules, LED and LCD panel data display, MP3 player, and power supply stability.

III. RESULT AND DISCUSSION

This research comprised a series of tests, including the evaluation of the ADXL335 and HMC5883L sensors, the assessment of the functionality of the DFPlayer Mini player, the analysis of WiFi UNDIP and Bluetooth HC-05 communication, the testing of EEPROM data storage, the investigation of gymnastics sample processing with downsampling, average pooling and data normalisation, and the evaluation of the overall movement scoring system for optimisation of the automatic rhythmic gymnastics apparatus prototype.

A. Sensor Testing

A programme of sensor testing was initiated in order to ensure the stability of sensor performance. The ADXL335 accelerometer was tested by moving the module forwards and backwards (X-axis), up and down (Y-axis), and left and right (Z-axis), while the HMC5883L magnetometer sensor was tested by

rotating the module left and right for heading calibration. The results of the ADXL335 accelerometer test are visualised in Figure 4a, which shows sharp oscillations on the dominant axis, while Figure 4b for the HMC5883L magnetometer shows variations in heading, enabling it to capture vibrations and changes in the rotational orientation of gymnastic movements. The dynamic response of the sensors to changes in linear acceleration and relative magnetic field changes is illustrated by this graphical representation. These changes are used to distinguish between low-impact and high-impact phases, and changes in body orientation during rhythmic gymnastics movements.

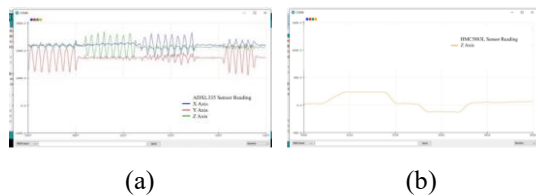


Figure 4. Graphical Visualisation of Sensor Readings (a) ADXL335 Sensor and (b) HMC5883L Sensor

B. Data Communication Testing

A series of tests were conducted to ensure the reliability of data transfer within the system, with a particular focus on inter-device communication. The Bluetooth master-slave communication testing using the HC-05 module at a baud rate of 38400 was conducted to ensure that the gymnastics assessment parameters were displayed consistently on the application and display panel. As illustrated in Figure 5a, the Delphi7 application displays the real-time data, while Figure 5b shows the P10 display panel synchronously displaying the gymnastics movement scores.

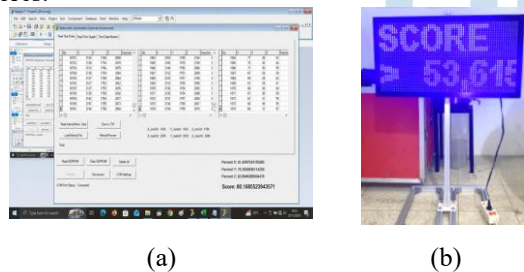


Figure 5. Bluetooth Master-Slave Communication Testing (a) Application Display and (b) Display Panel

The testing of client-server communication utilised RSSI (Received Signal Strength Indicator) measurements as an indicator of wireless signal strength, with RSSI values close to 0 dBm reflecting stronger signal intensity. As illustrated in Table 1, the outcomes of signal stability measurements at distances ranging from 1 to 6.5 metres are presented. The range of -1 to -75 dBm is indicative of a stable connection, characterised by the absence of delay or packet loss.

Table 1. Wi-Fi Signal Strength Test Results for Client-Server Communication

No	DISTANCE (CM)	GNAL STRENGTH (DBM)	REMARKS
1	0	-1	MOOTH CONNECTION
2	10	-17	MOOTH CONNECTION
3	20	-26	MOOTH CONNECTION
4	30	-32	MOOTH CONNECTION
5	40	-49	MOOTH CONNECTION
6	50	-56	MOOTH CONNECTION
7	100	-59	MOOTH CONNECTION
8	150	-61	MOOTH CONNECTION
9	200	-63	MOOTH CONNECTION
10	250	-69	MOOTH CONNECTION
11	300	-72	MOOTH CONNECTION
12	350	-75	MOOTH CONNECTION
13	400	-77	DATA TRANSMISSION DELAY OCCURRED
14	450	-	DATA TRANSMISSION DELAY OCCURRED
15	500	-83	DATA TRANSMISSION DELAY OCCURRED
16	550	-85	DATA FREQUENTLY DISCONNECTS AND RECONNECTS
17	600	-85	DATA FREQUENTLY DISCONNECTS AND RECONNECTS
18	650	DATA NOT SENT	DATA COMPLETELY DISCONNECTED

C. Data Storage Mechanism

The data storage mechanism has been designed to process and manage gymnastics movement sensor data in real time. The ESP32's internal storage mechanisms facilitate the retention of data from the transmitter module through a series of processes including parsing and temporary buffering in RAM. As illustrated in Figure 6, the ESP32's internal memory is allocated as follows: flash memory stores 952,512 bytes of program firmware, leaving 2,193,216 bytes of space, and 320KB of RAM, of which 167,532 bytes are used, including 47,532 bytes for global variables for system configuration and 120,000 bytes for sensor buffer arrays. The device under consideration provides storage options on 128KB external EEPROM. It is possible for users to elect to undertake non-volatile data logging when required. The EEPROM capacity has been

demonstrated to be capable of accommodating up to 120,000 bytes of sensor data.

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Sketch uses 952512 bytes (30%) of program storage space. Maximum is 3145728 bytes.
Global variables use 47532 bytes (14%) of dynamic memory, leaving 288148 bytes for local variables. Maximum is 327680 bytes.
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Figure 6. ESP32 Internal Storage

D. Analysis and Processing of Gymnastics Data Samples

The acquisition and analysis of raw data samples were conducted to identify the initial response characteristics of the sensors during the execution of gymnastics movements. The data was obtained from four parameters: the X-axis, Y-axis, Z-axis, and orientation direction as illustrated on Figure 7 (a), (b), (c) and (d), respectively. The 2012 SKJ warm-up movements yielded 7,210 data samples per parameter from 10 movement phases, which presents the low-impact acceleration pattern and variations in the direction of gymnastics warm-ups.

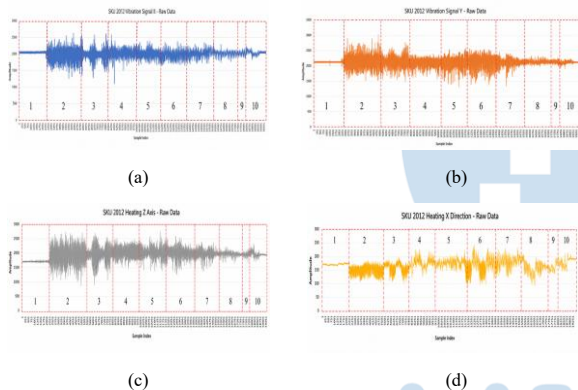


Figure 7. Raw Data from the 2012 SKJ Warm-up ADXL335 Sensor Output Signal (a) X-axis Acceleration, (b) Y-axis Acceleration, (c) Z-axis Acceleration, and (d) Direction Reading from the HMC5883L Sensor

The downsampling and average pooling processes were carried out by dividing the data index series into fixed blocks of 10 samples, where each block was reduced to a single average value, thereby reducing the total data by 90%. The data was obtained from four parameters: the X-axis, Y-axis, Z-axis, and orientation direction as illustrated on Figure 8 (a), (b), (c) and (d), respectively. As demonstrated in Figure 8, the raw signal graph appears dense, with the details of the movement phases being difficult to distinguish due to the large number of samples in each parameter. Following the implementation of the downsampling and average pooling processes, the 2012 SKJ heating data was compressed into 721 samples, thereby yielding a more lucid wave representation, as illustrated in Figure 8.

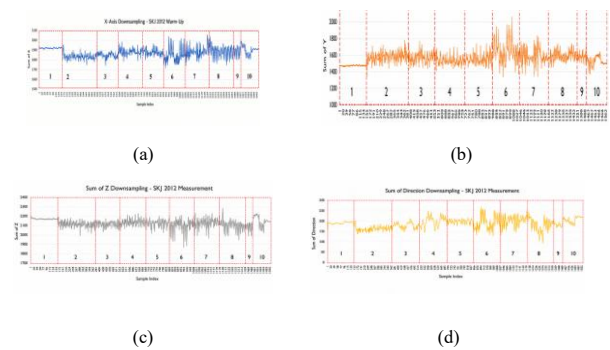


Figure 8. Downsampling Data with Average Pooling SKJ 2012 Heating ADXL335 Sensor Output Signal (a) X-axis Acceleration, (b) Y-axis Acceleration, (c) Z-axis Acceleration, and (d) Direction Reading from the HMC5883L Sensor

The data normalisation stage was carried out to linearly remap the downsampled data based on the minimum and maximum values per axis so that the amplitude of all parameters was projected to a range of 0-100. The direction parameter was not normalised to this range because the HMC5883L sensor reading values already directly represented the body's orientation. The graph in Figure 9 is still expressed in ADC output units with different ranges between axes, while Figure 9 displays the normalised data. The data was obtained from three parameters: the X-axis, Y-axis and Z-axis orientation direction as illustrated on Figure 9 (a), (b) and (c), respectively.

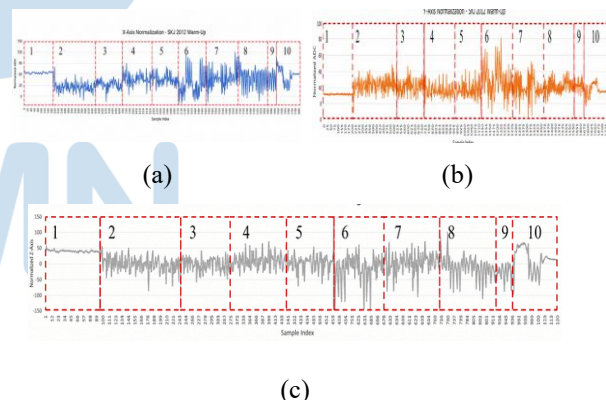


Figure 9. Normalized SKJ 2012 Data for Heating the ADXL335 Sensor Output Signal (a) X-axis acceleration, (b) Y-axis acceleration, and (c) Z-axis acceleration

E. Implementation and Evaluation of the Automatic Assessment System

The present research examined the implementation and evaluation of an automatic scoring system, with the objective of evaluating the system's performance in acquiring and interpreting body movements. Prior to the commencement of the testing phase, the participants were tasked with ensuring that both the transmitter and receiver modules were synchronised and connected in a correct manner. Thereafter, they proceeded to select the specific type of rhythmic gymnastics to be evaluated within the system.

Subsequent to the initiation of the session, the receiver module perpetually acquired data transmitted by the transmitter module until the gymnastics rhythm sequence reached its conclusion, at which juncture the automated data reception process was terminated.

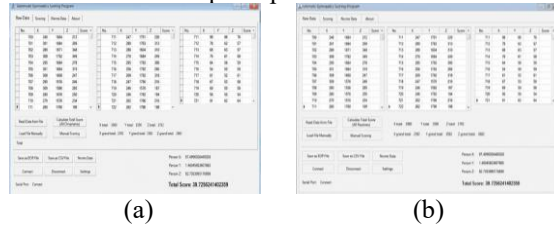


Figure 10. Testing of SKJ 2012 Warm-up Movements (a) Correct Movements and (b) Incorrect Movement

As shown in Figure 10, the system application incorporates a data processing flow involving a comparison with master data. The application displays the accuracy value per axis as X%, Y% and Z% with a weighting of 0.3 for each axis and 0.1 for the orientation direction. Figure 10a shows that the 2012 SKJ warm-up test, which incorporates movements that align with the master data, yielded a score of 85. Figure 10b, on the other hand, shows that diverging movements result in a significantly lower score about 39.72.

The research demonstrated that the automatic gymnastics assessment tool was capable of successfully acquiring data on movement dynamics and body orientation from the ADXL335 accelerometer and HMC5883L magnetometer sensors. The system has been demonstrated to possess the capacity to process large-scale sensor data with dense, fluctuating signals and difficult-to-read movement noise patterns into a more concise data representation, thereby reducing the computational load. Furthermore, the system is capable of distinguishing movement data patterns through the process of master data comparison, thereby producing quantitative scores that reflect the level of conformity. It has been demonstrated that significant differences between test data and master data trigger high errors and a decrease in movement validation accuracy.

IV. CONCLUSION

The research results indicate that the gymnastics movement assessment system installed in the back pocket of the participant's trousers, integrating the ESP32 microcontroller, the ADXL335 sensor, and the HMC5883L sensor, successfully acquired three-axis acceleration and body orientation data. The data was transmitted to the receiver module in real time for analysis by the application, thereby producing a numerical score for each gymnastics routine. The methodology employed to reduce data density by 90%, minimise noise and preserve movement trends involved implementing a downsampling technique. The data then consolidated into a single sample using an average pooling method, summarising 10 raw data samples into one. Data normalisation is integral to standardising the

scale range of all parameters. Subsequent comparison of the results allows the accuracy and error rate of the test to be calculated against the master data. The outcome of this process is a performance score that evaluates the degree to which the test movement aligns with the reference movement.

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