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Design and Implementation of Software and Angle Calibration System for an ESP32-Based Portable Digital Scoliometer

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Abstract

Scoliosis is a spinal deformity characterized by an abnormal lateral curvature of the spine and requires accurate early detection to prevent further complications. Conventional scoliometers are still widely used for initial screening; however, manual measurements often face limitations in reading precision and data recording efficiency. This study aims to design software and an angle calibration system for a portable digital scoliometer based on the ESP32 microcontroller. The developed system utilizes an MPU6050 sensor to detect trunk rotation angle, an LCD module as a display interface, and wireless communication for data transmission. The software implementation includes sensor data acquisition, angle processing using the Kalman Filter method, automatic zero-point calibration, battery monitoring, and communication with a web-based server through a RESTful API. The calibration system is designed to reduce initial offset errors and improve measurement stability. Testing results indicate that the system is capable of displaying angle measurements in real time, operating responsively, and transmitting data successfully to the server. The implemented calibration method also improves consistency and reliability of angle readings. Therefore, the developed portable digital scoliometer can serve as an effective solution for supporting scoliosis screening in a more practical and digitalized manner.

***Keywords**: Scoliosis, Digital Scoliometer, ESP32, Kalman Filter, Internet of Things*

1. Introduction

During adolescence, which is a transitional phase from childhood to adulthood, significant growth and development processes occur both physically and psychosocially. During this period, adolescents experience various changes, including changes in posture that need to be well-maintained as they will affect the body's condition in adulthood. Unergonomic sitting habits and improper use of bags can cause postural disorders in children, potentially increasing the risk of scoliosis. [1]. Scoliosis is a musculoskeletal disorder characterized by lateral curvature of the spine accompanied by vertebral rotation and three-dimensional changes in spinal structure. This condition can affect body posture, movement function, and quality of life if not properly addressed from an early age [2]. Scoliosis generally begins to develop during childhood or adolescence and in some cases goes undiagnosed until adulthood. Additionally, scoliosis can also appear in adulthood due to degenerative factors or changes in spinal structure[3]. If not detected early, scoliosis can cause various negative impacts, including a decrease in quality of life, disability, discomfort, back pain, body deformity, functional disorders, respiratory issues due to lung involvement, and psychological disturbances[4]. Therefore, early screening becomes a very important step to detect scoliosis conditions from a young age. This is due to the progressive nature of the disease, which can lead to more severe complications if not promptly and properly addressed [3].

One of the widely used initial screening methods for scoliosis is the Adams Forward Bend Test with the aid of a scoliometer to determine the Angle of Trunk Rotation (ATR). In this method, the patient is asked to bend forward, followed by a physical examination to measure the trunk rotation angle or ATR using a scoliometer as an initial indicator of spinal curvature abnormalities[5]. The measurement of the Angle of Trunk Rotation (ATR) using a conventional scoliometer still has several limitations[6]. Angle readings are generally done visually, which can potentially lead to differences in interpretation among examiners. In addition, the recording of measurement results is still done manually, which leads to a lack of efficiency in patient data management and increases the risk of loss and disorganization in medical documentation. The development of microcontroller technology enables the integration of various components such as sensors, actuators, and communication modules into a single efficient system, thereby opening up opportunities to enhance the quality of medical measuring instruments to be more accurate, practical, and integrated[7]. One of the most widely used microcontrollers is the ESP32, which has advantages in data processing capabilities and is equipped with built-in WiFi and Bluetooth modules, making it highly supportive of the implementation of Internet of Things (IoT)-based systems[8]. Meanwhile, the MPU6050 sensor is an inertial sensor consisting of an accelerometer and a gyroscope that functions to measure acceleration and angular velocity[9]. This sensor is capable of detecting changes in angle and tilt digitally with a good response rate. Therefore, the MPU6050 is widely used as a tilt indicator in various angle measurement applications due to its ability to produce data continuously and in real-time. The data generated by the sensor is then sent to a microcontroller for further processing in the measurement system[10].

In its implementation, motion sensor readings often experience disturbances such as noise, drift, and initial offset errors that can affect the accuracy of the measurement results. To address these issues, an appropriate data processing and calibration system is required. One of the methods that can be used is the Kalman Filter, which functions to reduce noise in angle readings and optimally estimate the system's state[11]. This method works by combining data from the accelerometer and gyroscope, resulting in a more stable and accurate angle estimation. In addition, an automatic zero calibration method is also applied to reduce initial angle errors before the measurement process is carried out. This calibration aims to maintain the initial condition of the measuring instrument to remain consistent, as well as to support the improvement of measurement quality in the digital scoliometer system[12]. Based on the aforementioned issues, this research aims to design software and an angle calibration system for a portable digital scoliometer based on ESP32. The developed system is expected to display the Angle of Trunk Rotation (ATR) measurement results in real-time, improve sensor reading stability, and support digital data storage thru network integration. With this system, the scoliosis screening process is expected to become more effective, practical, and modern in identifying scoliosis cases early on, thereby assisting medical personnel in making more accurate early detections[13].

2. Research Methodology

The research methodology used in this study is the engineering design method, which is an approach that focuses on the structured process of designing, implementing, and testing systems to meet user needs. [14]. This approach includes the stages of problem formulation, needs analysis, system design, implementation, as well as system performance control and evaluation. The research stages conducted include system needs analysis, hardware and software design, program implementation, sensor calibration, and equipment performance testing.

2.1 System Requirements Analysis

At this stage, the identification of system requirements capable of measuring the Angle of Trunk Rotation (ATR) digitally, being portable, and displaying measurement results directly is conducted. In addition, the system is designed to be able to store and transmit measurement data to the server via a wireless network. The main requirements of the system consist of several components as follows:

1. ESP32 microcontroller as the system control center
2. MPU6050 sensor as the tilt angle detector
3. 16x4 I2C-based LCD as the display medium
4. Navigation buttons as input for position selection and measurement process
5. Battery module as a portable power source
6. Wifi connection as the data communication medium to the server

2.2 Hardware Design

The hardware in this system is designed by integrating the MPU6050 sensor with the ESP32 microcontroller via I2C communication. Additionally, the 16x4 LCD is also connected using the I2C interface, making pin usage easier and improving the efficiency of connections between components. Input buttons are used as controls for selecting the measurement position and operating the start and stop processes. In addition, the LED indicator and buzzer are used as status indicators for the system, such as active condition, measurement process, or notifications of system success or failure.

2.3 Software Design

The software in this system is designed to process sensor data, perform calibration, and display and transmit measurement results. The overall workflow of the software is shown in Figure 1.

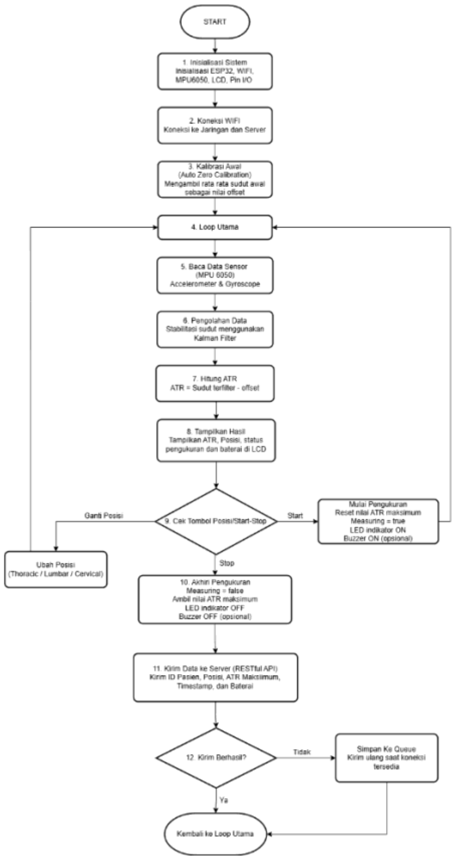

Fig. 1: Flowchart of Digital Scoliometer Software

The flowchart illustrates the main process of the system, starting from the device initialization stage, WiFi connection, and initial calibration (auto zero calibration), followed by the sensor data reading process, data processing using the Kalman Filter, and ending with the transmission of the measurement results to the server. The software is developed using Arduino IDE with the C++ programming language. The program is designed to control the entire system workflow in an integrated manner, from sensor data acquisition to network-based data communication.

The main functions in the software include:

1. Hardware initialization and WiFi connection
2. Reading accelerometer and gyroscope data from the MPU6050 sensor
3. Calculating the Angle of Trunk Rotation (ATR)
4. Data processing using the Kalman Filter method
5. Automatic zero calibration
6. Displaying measurement data on the LCD
7. Monitoring battery capacity
8. Sending measurement data to the server RESTful API

2.4 Angle Calibration System

In this system, the angle calibration process is performed automatically when the device is first turned on. Calibration is the process of comparing the value indicated by the measuring instrument with a standard value that has traceability to national or international standards [15]. In its implementation, the system will read angle data from the sensor thru several sampling sessions in a flat position, then calculate the average value as the initial offset. This offset value is used as the zero-degree reference in the measurement process, thereby reducing initial reading errors due to sensor bias. Thus, this calibration system plays a role in improving the accuracy and stability of angle measurement results on a digital scoliometer.

2.5 Sensor Data Processing

Data from the accelerometer and gyroscope are combined using the Kalman Filter method to reduce noise in angle readings, resulting in more stable and accurate data [11]. This method works by combining two sources of sensor data to obtain an optimal angle estimation in dynamic conditions. The sensor continuously reads position changes, then the system will record the angle values during the measurement process. The maximum angle value obtained during the process is used as the patient's Angle of Trunk Rotation (ATR).

2.6 System Testing

System testing is conducted to evaluate the overall performance of the device based on the following aspects:

1. Device function testing This test aims to ensure that all system components, such as sensors, LCD, buttons, buzzer, LED, and WiFi connection, function properly according to the design.

2. Angle reading response testing This test aims to measure the change in angle values when the device is tilted at several positions to determine the sensor's responsiveness
3. Data communication testing This test is conducted to ensure the successful transmission of measurement data to the server via the WiFi network.
4. Device portability testing This test aims to determine the device's performance when used with battery power, ensuring that the device can operate portably.

2.7 Data Analysis Techniques

The test data were analyzed descriptively based on the stability of the angle values, sensor reading response, data communication success, and overall system performance during the measurement process. The analysis was conducted to evaluate the performance of the software, the sensor data processing, and the designed automatic calibration system.

3. Results and Discussion

3.1 System Implementation

The developed digital scoliometer system has been successfully implemented and is capable of displaying measurement results in real-time via an LCD. The displayed information includes the Angle of Trunk Rotation (ATR) value, measurement position, patient name, and battery capacity percentage.

Fig. 2: ATR Measurement Results

Based on Figure 2, the system is capable of displaying an Angle of Trunk Rotation (ATR) value of 0.4° at the lumbar position in real-time thru the LCD. In addition to displaying the ATR value, the system also shows additional information such as patient identity and battery capacity status, making it easier for users to carry out the measurement process. During the data transmission process to the web system, a red LED will light up as an indicator that the measurement data is being sent via the WiFi network.

Fig. 3: ATR Measurement Results on Other Patients

Figure 3 shows the measurement process on other patients with different Angle of Trunk Rotation (ATR) values. The results show that the system is capable of reading changes in body angles responsively according to the measurement position performed. During the measurement process, a yellow LED will light up as an indicator that the device is measuring the patient.

3.2 ATR Value Category

ATR measurements in the system are categorized based on specific categories to assist in the initial scoliosis screening process. The categories of ATR values used in the system are shown in Table 1.

Table 1. ATR Value Category

ATR Value	Category
0° - 5°	Normal

> 5° - 8°	Observation
> 8°	Refer to a Specialist

Based on Table 1, the system divides the categories of Angle of Trunk Rotation (ATR) measurement results into several indication levels to assist in the initial scoliosis screening process. ATR values of 0°–5° are categorized as normal, values above 5° to 8° fall into the observation category, while values above 8° are recommended for further examination by a specialist doctor.

3.3 ATR Angle Test Results

The ATR angle testing was conducted to determine the system's ability to read body angle changes at several measurement positions. The test results are shown in Table 2.

Table 2. ATR Angle Test Results

No	Position	ATR Value	Remarks
1	Lumbar	0.4	Normal
2	Thoracic	1.4	Normal

Based on the test results in Table 2, the system is capable of reading ATR angles stably at several measurement positions. The values obtained indicate that the system can detect changes in body angles and display the measurement results in real-time.

3.4 Data Communication Test Results

Data communication testing is conducted to ensure the successful transmission of measurement data to the server via WiFi using a RESTful API.

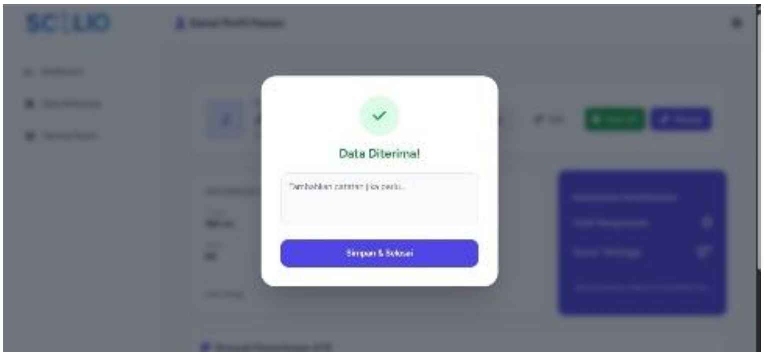

Fig. 4: Results of Data Communication Testing

Figure 4 shows the process of transmitting measurement data from a digital scoliometer to a web system via WiFi using a RESTful API. This process allows the measurement data to be stored and documented digitally in real-time.

3.5 System Discussion

Based on the results of implementation and testing, the designed software has been able to perform all the main functions of the portable digital scoliometer system. The integration of the ESP32 with the MPU6050 sensor provides the capability for digital and responsive angle measurement. The implementation of an automatic zero calibration system helps reduce initial reading errors due to sensor offset, while the Kalman Filter method can enhance data stability by reducing noise in angle readings.

In addition, the wireless data communication feature provides an advantage over manual scoliometers because the measurement results can be directly documented digitally. This can assist medical personnel in the process of recording, monitoring patient history, and improving the efficiency of examinations. Overall, the developed system demonstrates that the utilization of microcontrollers, digital sensors, and Internet of Things (IoT) technology can be a modern solution in supporting a more practical, responsive, and integrated scoliosis screening process.

4. Conclusion

Based on the design and implementation results that have been carried out, the software for the portable digital scoliometer based on ESP32 has been successfully developed in accordance with the research objectives. The system is capable of digitally reading the Angle of Trunk Rotation (ATR) using the MPU6050 sensor, displaying the measurement results in real-time thru an LCD, and sending the measurement data to a web system via WiFi. The application of the Kalman Filter method and auto zero calibration has proven to enhance the stability of sensor readings by reducing noise and initial offset errors during the measurement process. Additionally, the integration of an IoT-based system facilitates digital data documentation, thereby supporting the initial scoliosis screening process in a more practical and modern way. For the next phase of research, the system can be enhanced by adding local data storage features, using sensors with higher precision levels, and developing more interactive monitoring applications. In addition, further testing with a larger number of respondents is needed to obtain a more comprehensive system validation.

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