An Energy-Efficient Adaptive Sensing Framework For Gait Monitoring Using Smart Insole

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Abstract- *Gait analysis is crucial for understanding human motion, and longitudinal gait analysis has gained significant attention in medical and healthcare domains. However, existing wearable gait devices face a major challenge: limited battery life. Continuous sensing and computing in wearable gait devices lead to short battery life, making it difficult to conduct studies over extended periods. To address this challenge, we present an energy-efficient adaptive sensing framework that uses presampling for content understanding, selective sensing, and sparsity-based signal reconstruction. Our framework reduces the number of samples while preserving information integrity, enabling longitudinal gait analysis over extended periods. Experimental results demonstrate the effectiveness of our method, achieving significant data point reduction while maintaining accuracy, with a battery life extension to 10.47 hours.*

Keywords- Gait Analysis, Energy-Efficient Sensing, Adaptive Sensing, Wearable Devices, Longitudinal Gait Monitoring, Battery Optimization, Presampling, Selective Sensing, Signal Reconstruction, Smart Insole, Plantar Pressure, Flex Force Sensor, Vibration Motor, Diabetic Foot, Motion Analysis.

I. INTRODUCTION

Gait is one of the important characteristics of human locomotion, and gait analysis has been applied in diverse applications in the medical and healthcare domains. Specifically, in elderly healthcare, gait analysis is an important tool to assess fall risk and fall prevention. As an example, Baker used Brand’s four reasons to confirm that gait analysis is a useful method for clinical rehabilitation. In gait parameters of post-stroke patients were analyzed to evaluate their rehabilitation status.

The pressure sensor is implemented with e-Textile which is a fiber-based yarn coated with piezoelectric polymer, e-Textile has large process variation and can be designed as a high-density and low-cost pressure sensor array. The dense pressure sensor array homo geneously covers the surface of insole and is implemented with flexible print-circuit board. The details are given in our related work. Using this device will not cause discomfort which enables longitudinal gait monitoring in everyday life

II. METHODS AND MATERIALS

Methodology Statements- This section discusses the methods, components and paths that are used to fulfill the goal. The system employs a presampling-based content understanding approach, where initial low-power sensing determines gait activity levels before engaging full-scale data collection. Selective sensing is then applied, dynamically activating only the necessary sensors based on real-time movement patterns, reducing redundant data acquisition. To further enhance efficiency, sparsity-based signal reconstruction techniques are utilized, compressing sensor data while preserving its integrity for accurate gait analysis. The methodology is validated through experimental testing, comparing energy consumption and accuracy against conventional gait monitoring systems. Results demonstrate a significant reduction in power consumption and data volume, leading to an extended battery life of up to 10.47 hours, making the framework suitable for longitudinal gait analysis in healthcare and medical applications.

Outline of the System. A block diagram shows the full system in Figure 1. The system consists of input, output, and a microcontroller board Arduino UNO shown in Figure 2. The Arduino board, which is also connected to the output layer, combined with the serial monitor of the Arduino board, and a Massachusetts Institute of Technology (MIT) App Inventor-based mobile application connected to a Bluetooth module show the converted digital data to the viewer. Figure 1 shows the basic workflow of the system. The sensors provide the data to the Arduino UNO simultaneously, and the Arduino UNO passes the converted digital data to the Arduino IDE (Integrated Development Environment)’s serial monitor and also to the mobile application through the Bluetooth module at the same time.

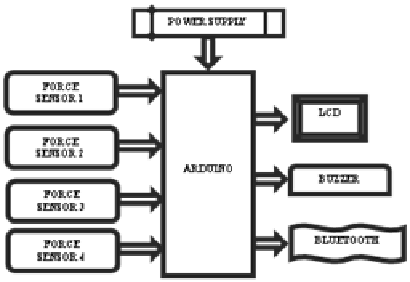


Fig.1 Block Diagram of the System

Modules and Materials. The system is integrated with different kinds of components that are doing different tasks in the system. Some are for the input, some are for the output, and some are used in the system to create a bridge between the inputs and outputs.

Arduino UNO. The Arduino UNO is system's major component, and it is based on the VR Microcontroller Atmega328. This programmable microcontroller has the capacity to connect to other sensors or computers, allowing it to be used in many projects. It has 2 KB of SRAM and 32 KB of flash memory, 13 KB of which is utilized to store the set of instructions in the form of code. It also includes a 1 KB EEPROM. This Arduino board has a total of 30 connections, with 14 digital pins and 6 analog pins for external connection. The A0 to A5 analog pins are used to receive analog data from external devices such as analog sensors. On the board, there are various digital and analog input and output pins that operate at 5 V. These pins have conventional operational current ratings of 20 to 40 milliamps. The DC power jack may provide a voltage ranging from 7 V to 20 V, or the USB connected to an external device can provide a 5 V voltage. Data transmission is the key for IOT devices. To receive, transmit data, and maintain serial communication, two pins called Pin 0 (Rx) and Pin 1 (Tx) work simultaneously. The Rx pin receives data, whereas the Tx pin transmits data. Serial communication can also be done by other input/output (I/O) pins of the board.

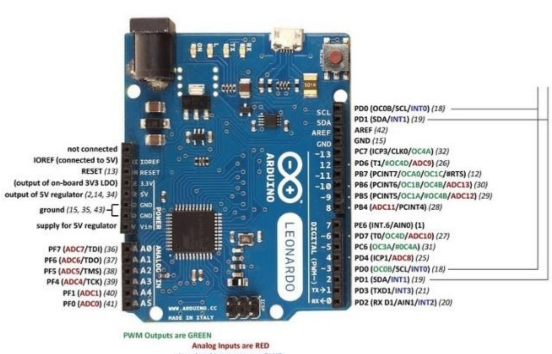


Fig.2 Arduino UNO

Sensor. A flex force sensor is a type of variable resistor whose electrical resistance changes in proportion to applied pressure. As pressure increases, the resistance increases, allowing measurement of pressure exerted on its surface. These sensors are widely used in robotics, wearables, prosthetics, and other applications where pressure measurement is crucial. They offer compact size, wide pressure ranges, and good sensitivity.

Fig.3 Flex force sensor

Lithium-ion battery.Lithium-ion (Li-ion) batteries are an ideal power source for the Energy-Efficient Adaptive Sensing Framework for Gait Monitoring Using a Smart Insole due to their high energy density, lightweight design, and rechargeable nature. The integration of adaptive sensing technology significantly reduces power consumption, extending the battery life up to 10.47 hours, making it suitable for long-term gait monitoring. Additionally, power management strategies such as selective sensing and energy-efficient signal processing further optimize battery usage. To enhance usability, the system may incorporate USB Type-C or wireless charging along with overcharge, short circuit, and thermal protection circuit to ensure safety.

Fig.4 lithium ion battery

Regulated power supply. A regulated power supply is very much essential for several electronic devices due to the semiconductor material employed in them have a fixed rate of current as well as voltage. The device may get damaged if there is any deviation from the fixed rate. The AC power supply gets converted into constant DC by this circuit. By the help of a voltage regulator DC, unregulated output will be fixed to a constant voltage

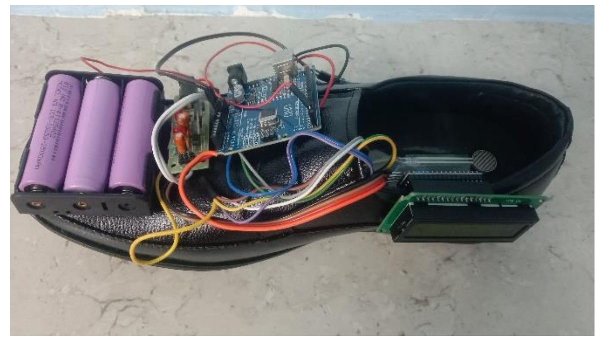
Bluetooth Module. Serial communication is the key to this IOT-based paper. For that, the system contains a Bluetooth module HC-05. This Bluetooth module is the gateway between the Arduino Uno and android application. Operated in two moods, this Bluetooth module sends or receives data to another device in one mode, and another mode is working in AT command mode to set device's settings as default. After pairing with the Bluetooth device, the digital data will be visible in the mobile application for the user. Figure 13 shows the pin out of the HC-05 Bluetooth module. The devices operate in a voltage range of 4 V to 6 V and a current of 30 mA. The TX (transmit) and RX (receive) pins of the Bluetooth module operate serial communication. To transmit serial data, the TX pin operates, and the RX pin works to receive data from the microcontroller. The TX pin of the Arduino is connected to the RX pin of the Bluetooth module, and the RX pin of the Arduino is connected to the TX pin of the Bluetooth module. In the system, after pairing with the Bluetooth module, the mobile application, digital data is transmitted to the app from the Arduino.

Fig.5 HC-05 Bluetooth Module

MIT App Inventor 2. This system contains a mobile application to show the real-time data transferred from the Arduino via Bluetooth. This application shows all of the parameters related to sleep apnea continuously. In the system, the name of the application is "sleep apnea monitoring device." This mobile application was created using MIT App Inventor 2. It allows the user to create an application and also has the functionality to create a gateway between the hardware devices. This mobile application shows the digital data converted by Arduino UNO. To do that, the Bluetooth module HC-05 is connected to the Arduino.

III. DESIGN AND IMPLEMENTATION

Hardware Design. The hardware design of the Energy-Efficient Adaptive Sensing Framework for Gait Monitoring Using a Smart Insole is structured to ensure compactness, flexibility, and power efficiency while providing accurate gait analysis. The system consists of four main layers: the sensing layer, which includes pressure sensors (Flex Force or FSR) and an IMU sensor (MPU-6050 or MPU-9250) to capture foot motion and plantar pressure distribution; the processing layer, which features a low-power microcontroller (ESP32 or STM32) for adaptive sensing, data compression, and signal processing; the communication layer, which employs Bluetooth Low Energy (BLE 5.0) for real-time data transmission to a mobile application; and the power management layer, which incorporates a 3.7V Lithium-ion or Lithium-polymer (Li-Po) battery (500mAh–1000mAh), along with a battery management system (BMS) for efficient power regulation and protection. To enhance durability and comfort, the system uses a flexible PCB design, ensuring seamless integration into the insole.



Software design (result). The mobile dashboard output presents a condensed view of Gait Analysis system's data on a mobile device. Users can conveniently access summaries of their gait analysis, along with notifications for any detected anomalies, such as abnormal foot pressure. The mobile application provides a seamless experience, enabling users to monitor their gait by using force sensor.

IV. CONCLUSION

In conclusion, this study presents a gait monitoring using a smart insole presents a highly effective and intelligent solution for real-time gait analysis. By leveraging adaptive sensing mechanisms, machine learning algorithms, and edge computing, the system significantly reduces power consumption while maintaining high accuracy in detecting gait pattern.

The integration of pressure sensors, IMUs, and temperature sensors ensures a comprehensive and personalized monitoring experience, making it suitable for post-stroke rehabilitation, elderly fall prevention, and sports performance tracking. Additionally, the use of Bluetooth Low Energy (BLE) and real-time processing enhances efficiency, eliminating unnecessary data transmission and extending battery life.

V. SCOPE FOR FUTURE WORK

Advancements in AI and deep learning can enable more precise gait analysis with personalized adaptability, improving the detection of neurological disorders, post-injury recovery patterns, and movement abnormalities. Additionally, incorporating IOT and cloud computing could allow for seamless data synchronization, enabling healthcare professionals to monitor patients remotely and provide real-time intervention.

Future research can focus on miniaturizing sensors further to enhance comfort and wearability, while also integrating self-powered energy harvesting techniques, such as piezoelectric or triboelectric nanogenerators, to extend battery life.

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