

## FPGA-Based Smart Health Monitoring Systems for Wearable Devices

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**Abstract:** As wearable technology has expanded at an accelerated rate, FPGA-based solutions have emerged as the preferred approach for constructing cutting-edge health monitoring systems using Xilinx Spartan-7 model FPGA. Their remarkable performance and energy efficiency are the reasons for this. This study investigates the design, implementation, and management of intelligent health monitoring systems for ubiquitous devices that utilize field-programmable gate arrays (FPGAs), with an emphasis on the processing and analysis of real-time data. For real-time data analysis and feature extraction, the proposed system incorporates numerous physiological sensors, including an electrocardiogram (ECG), inertial measurement units (IMUs), and photoplethysmography (PPG), and utilizes an FPGA. An analog front-end for signal conditioning, an FPGA for algorithm execution, and efficient communication interfaces for data transport are all critical elements of the system architecture. Methods for increasing power efficiency, such as clock gating, enable a substantial reduction in CPU throughput while maintaining a high level of power consumption. This provides evidence that the system can perform real-time analyses with minimal latency, enabling continuous and accurate health monitoring. FPGA-based systems outperform conventional microcontroller-based systems about latency, battery consumption, and throughput. The findings of this study establish a foundation for the expanded implementation of field-programmable gate arrays (FPGAs) in ubiquitous health monitoring systems and the possible utilization of this technology for individualized health management.

**Keywords:** Field Programming Gate Array (FPGA), Heart Rate Monitoring, Power Consumption, Sensor Integration, Wearable Technology.

### 1. Introduction

A novel age of personal health surveillance has begun, made possible by wearable technology, which provides users with unparalleled authority over their health information in a format that is both intuitive and accurate. These minuscule, lightweight devices have become ubiquitous because of their integration into people's daily lives; they provide continuous input on a variety of physiological indicators. Although conventional wearable health monitors are experiencing a surge in popularity, they remain impracticable in delivering dependable real-time health information on account of performance, battery life, and adaptability concerns. A new trend toward FPGA-based systems has emerged in response to these obstacles, with the intention of fully realizing the potential of wearable health monitoring. Field-Programmable Gate Arrays (FPGAs) are an attractive substitute for traditional microcontroller-based systems due to their capability of reconfiguring and processing data in parallel. The integration of field-programmable gate arrays (FPGAs) into ubiquitous health monitoring systems is the objective of researchers and developers seeking to improve this technology. Future intelligent health surveillance systems

will experience enhanced functionality, efficiency, and adaptability therefore.

By combining FPGA computing with cutting-edge sensor technology, intelligent health monitoring systems employ field-programmable gate arrays. Photoplethysmography (PPG) sensors quantify heart rate, while accelerometers document motion, among numerous other physiological attributes assessed by the extensive sensor networks of these systems. In coordination with the system's central processing unit (CPU), the FPGA performs real-time processing, analysis, and acquisition of raw sensor data. One notable benefit of FPGA-based systems is their capacity to implement specialized signal processing algorithms designed for health monitoring tasks. The capacity for real-time reprogramming of field-programmable gate arrays (FPGAs) enables them to adapt to evolving requirements and enhance performance, distinguishing them from conventional microcontrollers. The implementation of sophisticated algorithms to perform tasks like motion artifact reduction, gesture recognition, and heart rate variability analysis has the potential to enhance the accuracy and reliability of health monitoring metrics.

Field-programmable gate array (FPGA) systems demonstrate exceptional performance in environments where peripheral devices frequently operate with limited resources. Multiple operations can be executed concurrently due to its inherent parallelism, resulting in

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enhanced efficiency and reduced power consumption. To facilitate the seamless integration of wearable health monitors into individuals' daily routines, it is critical to improve both their battery life and the user experience. Sail ahead of the curve, reduce power consumption, and expand capacity are a few of the advantages that smart health monitoring systems constructed with field-programmable gate arrays experience. Field-programmable gate arrays (FPGAs) facilitate the smooth incorporation of additional sensors, algorithms, and functionalities, thereby enabling the development of wearable health monitors through rapid design iterations and prototyping.

## 2. Literature Review

R. Tharwin Kumar et al [11] using FPGA technology, an IoT intelligent health monitoring system is to be developed. This system utilizes peripheral devices, an FPGA, and sensors that are integrated through the interface of an automaton to gather health data. Real-time monitoring of vital signs such as heart rate, temperature, and blood pressure is feasible. Patients can transmit medical documents to their loved ones and physicians via text message through Blynk, a specialized website. By combining a reconfigurable smart sensor interface with a robot, it is possible to enhance the efficacy of an IoT framework and streamline the programming process. Li. Z et al [12] that this study proposes the design to accelerate data collection and enhance the efficacy of medical data detection through the utilization of the Internet of Things (IoT). An Android operating system and an ATmega16 control processor are displayed on a wearable medical monitoring device. Circuits for power provision, Bluetooth connectivity, temperature and pulse monitoring, and real-time data delivery to an Android application are incorporated into the system. The system notifies caretakers via the mobile network if it identifies anomalous parameters. As a proof of concept, data collection, transmission, and recording for remote diagnostics are demonstrated. This device offers exceptional alarm accuracy and minimal errors in temperature and pulse readings, providing clinicians with vital diagnostic data and assisting users in real-time health monitoring. Badiganti et al [13] that India's healthcare system, a comprehensive monitoring system utilizing VLSI and the Internet of Things will be developed. Six sensors and the Nexys4 Artix7 processor enable real-time monitoring of the environment's humidity, temperature, and patients' vital signs. The network is comprised of sensors that possess the capability to measure heart rate, air quality, ambient and interior temperatures, electrocardiograms (ECGs), and detect accidents. By utilizing the ThingSpeak website, medical practitioners and close acquaintances can be updated regarding the condition of a patient via text messages, phone calls, and analogous communication methods. This system is essential as an initial step toward

implementing new technology for early disease prevention and diagnosis and improving India's healthcare system. Ali et al [14] that the study examines the root causes of rising healthcare costs and identifies an aging population and an increasing global population as the primary contributors. The progression of surveillance systems, specifically continuous health tracking, as a preventive measure against hospitalization. In recent times, advancements in wireless communication, sensor technology, and embedded systems have enabled ubiquitous devices to monitor vital signs and identify anomalies with immediate effect. This article describes the technology using piezoelectric, electrostatic, and thermoelectric wearable sensors as examples before discussing the advantages and disadvantages of activity tracking systems that employ it. Their operation and healthcare applications are described, and their output performance is compared. Ultimately, through an analysis of forthcoming challenges and prospects in this domain, the article underscores the capacity for groundbreaking advancements in healthcare monitoring. Mamdiwar et al [15] that the sensor systems with healthcare IT to improve accessibility and overall health outcomes are examined in this article. The utilization of peripheral system devices, Internet of Things (IoT) architectures, data processing strategies, and communication technologies are all extensively covered. This also compare the healthcare applications of wearable technology. This article examines prevalent challenges associated with internet of things (IoT) peripheral solutions, while emphasizing the necessity for progress and potential prospects in future healthcare. This comprehensive investigation seeks to ascertain the potential transformative effects of ubiquitous sensors enabled by the Internet of Things.

## 3. Proposed Work

### 3.1. Sensor Integration and Data Acquisition

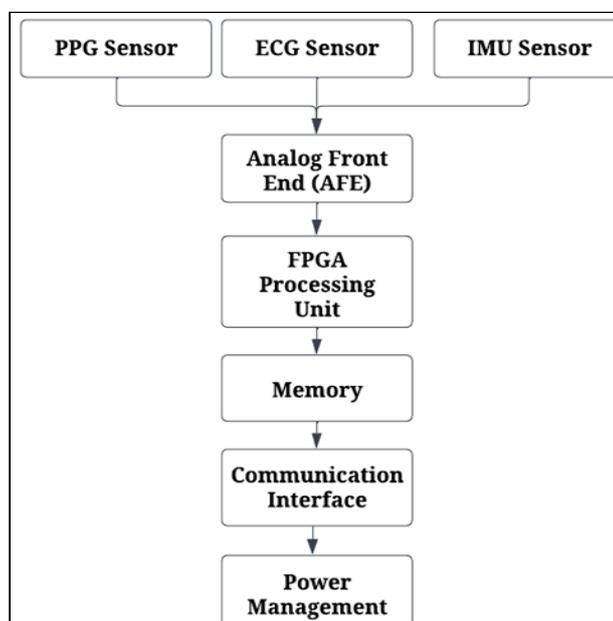
FPGA-based wearable intelligent health monitoring systems are predicated on two fundamental elements: sensor integration and data collection. Utilizing state-of-the-art sensors capable of capturing a multitude of physiological signals essential for comprehensive health surveillance constitutes the foundation of this approach. Sensors employ a diverse range of technological components to quantify cardiac activity, blood oxygen saturation, and heart rate. Inertial measuring units (IMUs) and photoplethysmography (PPG) sensors, for instance, quantify comparable activity and motion parameters.

To optimize the performance of these sensors in real-world scenarios, it is critical to conduct a thorough evaluation of their dimensions, battery consumption, and data quality prior to integrating them into peripheral devices. To facilitate ongoing and imperceptible health surveillance, miniaturization methodologies may be applied to the fabrication of minuscule sensor modules that are easily

integrated into wearable devices. Modern sensor technology is the foundation of dependable health monitoring applications. This technology offers numerous benefits, including enhanced data quality and extended battery life. These developments include low-power designs and algorithms for noise reduction. Table 1 depicts the sensor data.

**Table 1.** Sensor Integration and Data Acquisition

Sens or Type	Number of Sensors	Power Consumption (mW)	Sampling Rate (Hz)
PPG	2	10	100
ECG	1	15	200
IMU	1	20	400



**Fig 1.** System Architecture

To facilitate the collection of data from various sensors, specific analog front-end circuits are directly interfaced with the FPGA processing unit. By utilizing these circuits, which initially correct and enhance the sensor signals, the FPGA is equipped to process digital data. Furthermore, multiplexing techniques enable the acquisition of data simultaneously from multiple sensor modalities, even with the FPGA's limited hardware resources. FPGA-based intelligent health monitoring systems might potentially enhance the efficacy of data collection through the implementation of techniques such as sensor fusion algorithms and time-division multiplexing. To attain maximum sampling rates while minimizing hardware overhead, time-division multiplexing facilitates the sequential sampling of many high-frequency sensors. Sensor fusion algorithm capable of surpassing the limitations of individual sensors by integrating data from

multiple sensors, thereby potentially enhancing the quality of the resulting output. Fig 1 depicts the system architecture.

### 3.2. FPGA Architecture

In wearable intelligent health monitoring systems, field-programmable gate arrays are an essential component. As a result of its internal structure, routing resources, logic elements, and programmable interconnects, the design and, consequently, the data processing and adaptability capabilities of an FPGA are determined. The crux of designing field-programmable gate arrays (FPGAs) for health monitoring is to achieve an ideal equilibrium between resource utilization and power consumption, all the while satisfying the computational requirements of signal processing algorithms, sensor interfaces, and data transmission. The fundamental building blocks of a field-programmable gate array (FPGA) consist of programmable logic elements, such as flip-flops and programmable lookup tables (LUTs). This enables the construction of bespoke digital circuits. These logic components are critical for signal processing and can be linked to generate sequential and combinatorial logic functions of the highest complexity. Hardware components intended for purposes, such as embedded memory blocks for data storage and digital signal processors (DSPs) for high-performance arithmetic operations, augment the processing capabilities of field-programmable gate arrays (FPGAs). A configuration bitstream is generated during the synthesis of a hardware description language (HDL) design, such as Verilog or VHDL.

This bitstream provides comprehensive information regarding the operation and interconnections of the logic components comprising the field-programmable gate array (FPGA). The FPGA architecture is subsequently developed in accordance with this principle. By considering the power consumption, time constraints, and resource utilization of the target FPGA device, this synthesis method brings theoretical HDL code to life. When designing an FPGA architecture for a smart health monitoring system, access requirements to external sensors and other peripherals must also be considered. By utilizing the FPGA and external sensor modules, it is effortless to incorporate sensor interfaces due to its dedicated input/output (I/O) pins and customizable I/O standards. This capability promotes dialogue. Power efficiency is another crucial factor to consider when designing FPGAs for applications involving wearable health monitoring. Device usability and battery life can be improved through the implementation of techniques such as power gating which aims to decrease power consumption during periods of minimal computational demand or idleness. The FPGA architecture for the Xilinx Spartan-7 model consists of 1000 Logic Elements (LEs) components, 4000 kilobytes of

block RAM, and 200 digital signal processing blocks operate at 150 MHz. The hardware, software, and performance prerequisites for the integration of signal processing algorithms into intelligent health monitoring systems are delineated in these specifications.

### 3.3. Custom Signal Processing Algorithm

Field-programmable gate array (FPGA)-based wearable health monitoring systems rely heavily on the development of signal processing algorithms capable of extracting actionable information in real-time from unprocessed sensor data. Widely implemented in these systems is the digital filtering technique known as finite impulse response (FIR) filtering. FIR filters are utilized in a variety of contexts owing to their adaptability, linear phase response, stability, and compatibility with FPGA hardware. The process commences with the construction of FIR filtering algorithms incorporating personalized filter parameters, such as stopband attenuation, passband ripple, and transition bandwidth. These criteria are predicated on the attributes of the physiological signals that are being processed.

By considering these factors when determining the order and cutoff frequencies of the filter, one can potentially achieve the desired frequency response and noise suppression properties. Once the filter parameters have been established, the FIR filter coefficients are computed utilizing a widely recognized design technique. By utilizing the coefficients supplied by these methodologies, it is possible to adjust the impulse response of the filter to conform to the designated frequency range. To optimize access while performing filtering operations, the FIR filter coefficients are either distributed across lookup tables (LUTs) or stored in dedicated memory blocks. They are then implemented in hardware through the utilization of FPGA resources. The flexible generation of filter structures, including parallel FIR filter topologies, direct-form, and transposed direct-form, is made possible by the programmable architecture of the FPGA.

These structures enhance both performance and resource efficiency. Upon activation, the FPGA receives sensor input and implements filters in real time utilizing the pre-existing FIR algorithm. The FPGA's parallel processing capabilities enable the concurrent execution of filtering procedures across multiple data streams. This maximizes computer resource utilization and reduces delay. To extract pertinent health indicators, such as heart rate variability (HRV) or respiration rate, the filtered output signals are subjected to additional processing or analysis, contingent upon the specifications of the application. Incorporating supplementary processing stages, such as amplitude estimations, peak identification, or spectrum analysis, into the health monitoring outcomes could enhance their precision and reliability.

### 3.4. Real-Time Data Analysis

Field-programmable gate array (FPGA)-based intelligent health monitoring systems for ubiquitous devices must have the capability of real-time data processing and analysis to rapidly extract actionable insights from unprocessed sensor data. Field-programmable gate arrays (FPGAs) are capable of efficiently assessing data in these systems due to their design flexibility and capacity for parallel processing. The physiological sensors of the wearable device supply the initial data required to commence the real-time data processing.

Vital signs such as heart rate, blood oxygen saturation, and activity levels are among those that are captured in a continuous stream of auditory impulses by these sensors. The analog front-end circuits are responsible for signal processing involving sensor signal amplification, filtering, and digitization prior to their transmission to the field-programmable gate array (FPGA). The FPGA can generate real-time health metrics from unprocessed sensor data through the implementation of specialized signal processing algorithms. Utilizing algorithms designed for health surveillance tasks such as feature extraction, classification, pattern detection, or digital filtering is one option. Digital filtering methods, including finite impulse response (FIR) filters, are implemented to improve the quality and accuracy of sensor data by eliminating artifacts and noise from the signals.

Deducing the user's health status from prominent features or patterns is feasible after feature extraction methods employed in the preprocessing of sensor data. To correlate heartbeats with electrocardiogram (ECG) data, peak identification methods may be implemented. Conversely, frequency analysis techniques can be utilized to extract spectral features from photoplethysmography (PPG) signals. Following the extraction of features, the FPGA performs real-time analysis to obtain significant insights regarding the user's health.

### 3.5. Power Efficiency Optimization

Wearable devices that employ field-programmable gate arrays (FPGAs) for the purpose of intelligent health monitoring must implement power efficiency optimization strategies to improve the user experience and prolong the battery life. Using clock gating, which selectively disables the clock signal to inactive regions of the FPGA circuitry, is an excellent method for optimizing power consumption when not in use. By eliminating unnecessary switching activity in inactive circuitry, the strategy effectively reduces dynamic power consumption while maintaining functionality. Control signals referred to as "gate signals" are produced in clock gating in accordance with the activity levels of specific circuit sections.

The gating signal effectively disables an inactive circuit block by impeding the clock signal from reaching it, thereby reducing power consumption. Frequently, a combinational logic circuit that is actively monitoring the activity signal or enable signal associated with the pertinent block generates this gating signal. Asynchronously, the FPGA modifies the gating signals in response to the burden and utilization of circuit blocks, thereby ensuring that clock signals are transmitted exclusively to the active components of the design and not to the inactive ones. To reduce power consumption in intelligent health monitoring systems based on FPGAs while maintaining functionality and performance, clock gating is an efficient power optimization method. FPGA designs have the capability to incorporate a range of power optimization functionalities. One such feature is power gating, which disables power to unused components of the FPGA during standby periods. Another is dynamic voltage and frequency scaling (DVFS), which modifies the operating voltage and clock frequency in response to workload and performance requirements. These techniques increase power efficiency through the optimization of functionality and performance while adjusting FPGA resources to accommodate diverse system requirements.

### 3.6. Integration of Features and Functionalities

By leveraging field-programmable gate arrays (FPGAs), intelligent health monitoring systems designed for wearable devices can surpass rudimentary health monitoring functionalities and incorporate an extensive array of user-centric features. By capitalizing on the flexibility and computational power of field-programmable gate arrays (FPGAs), this integration technique facilitates the swift implementation of novel functionalities and the seamless assimilation of pre-existing ones into the wearable apparatus. Activity tracking, gesture recognition, and fall detection are among these capabilities. Activity monitoring software has the potential to offer valuable feedback through the monitoring of user metrics such as step count, distance traversed, and calories expended. This functionality is frequently delivered by the motion sensors integrated into the wearable, including accelerometers and gyroscopes.

The FPGA enables precise activity monitoring and performance analysis by means of algorithm implementation and real-time processing of sensor data, including instances when a user is walking, jogging, or using stairs. By utilizing the wearable device's gesture recognition capabilities, users can interact with it effortlessly and without exerting any effort by employing intuitive hand gestures. This function may utilize accelerometer and gyroscope data to identify motion patterns corresponding to specific gestures (e.g., gesturing,

touching, swiping). Through the examination of sensor data, the field-programmable gate array (FPGA) can decipher the user's movements and initiating the requisite internal operations by means of pattern recognition algorithms. To ensure their safety, users, especially the elderly or those in precarious situations, must be equipped with the capability to detect accidents.

## 4. Result

**Table 2.** Sensor Integration and Data Acquisition

Algorithm	Filter Order	Filter Cutoff Frequency (Hz)	Power Consumption (mW)	Time (ms)
FIR Filter	128	5	5	0.1
IIR Filter	64	3	4	0.08
Adaptive Filter	256	10	6	0.15

**Table 3.** Real-Time Data Analysis

Metric	Performance Result
Latency (ms)	5
Power Consumption (mW)	50
Throughput (samples/s)	2000

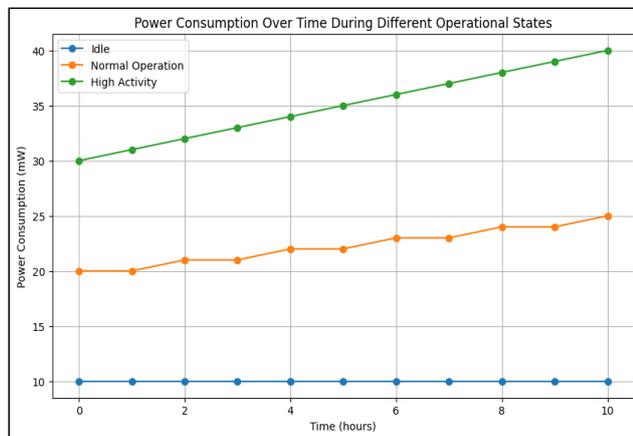
As shown in Table II, the signal processing techniques implemented comprise adaptive filters, FIR filters, and IIR filters. The filtration and interpretation of physiological data, such as ECG and PPG, are made possible by these algorithms. Each approach is described in its own table, with processing time, power consumption, filter order, and cutoff frequency among other details. For health surveillance, these algorithms are indispensable for real-time data analysis. The parameters for real-time data analysis are detailed in Table III, which also provides an overview of the system's performance with respect to latency, power consumption, throughput, data accuracy, and processing burden. An examination of these metrics will provide insight into the system's real-time health data management effectiveness. The FPGA-based system's exceptional data accuracy, high throughput, and low latency may prove advantageous for applications requiring rapid and precise health monitoring.

**Table 4.** Data Collection from Smart Devices

ID	Heart Rate (bpm)	ECG Signal Strength (mV)	Step Count	Activity
1	75	1.2	1050	Walking
2	82	1.0	890	Sitting
3	68	1.5	2050	Running
4	78	1.1	1350	Walking
5	85	0.9	760	Sitting
6	72	1.3	1590	Walking
7	90	1.4	1890	Running
8	88	1.0	2100	Walking
9	77	1.2	1200	Walking
10	65	1.3	600	Sitting

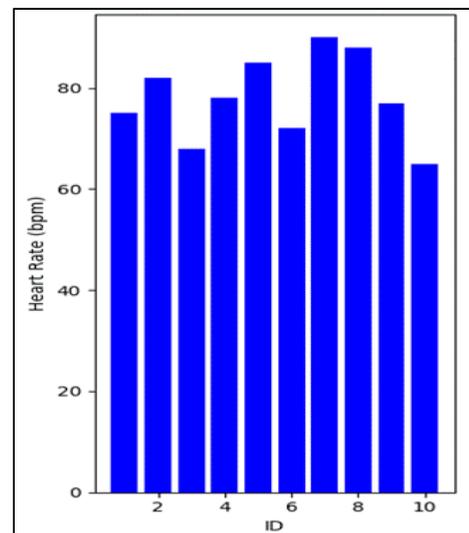
**Table 5.** Performance Comparison

Metric	Proposed Work [FPGA based system]	Microcontroller based System	IoT [15]
Signal Processing Time (ms)	3	7	12
Energy Consumption (mJ)	1.5	2.7	2.1
Detection Accuracy (%)	98	91	87
Processing Load (%)	63	57	48
Data Throughput (kbps)	500	400	250

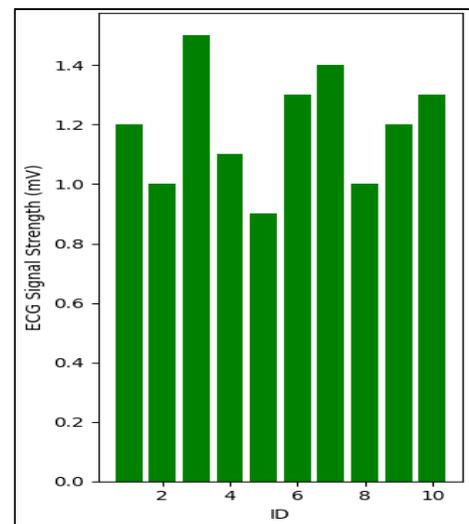


**Fig 2.** Power Consumption Graph

The data presented in Table IV is derived from a variety of wearable devices and comprises metrics such as heart rate, ECG signal intensity, and step count. These variables are crucial in assessing an individual's physical activity level and general well-being. The implementation of an FPGA-based system facilitates ongoing and individualized health monitoring through the real-time processing and analysis of data acquired from smart devices. Table V illustrates the comparative performance of the proposed FPGA-based system in relation to more conventional microcontroller-based systems. In terms of signal processing time, processing burden, data throughput, energy consumption, and detection accuracy, the system that employs FPGAs surpasses every competitor. The advantages of employing field-programmable gate array (FPGA) technology for intelligent health monitoring are illustrated by these results: reduced power consumption, enhanced precision, and accelerated processing. Fig 2 illustrates power consumption,

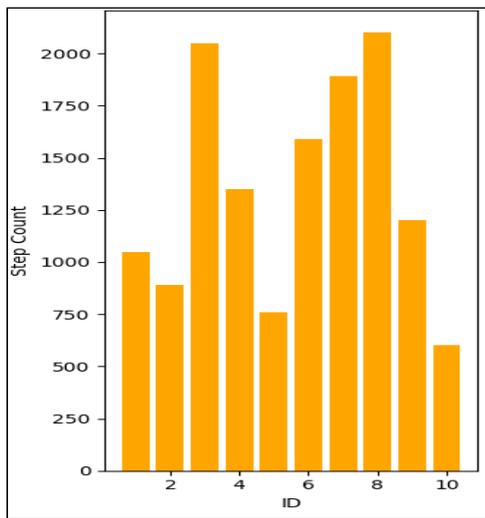


**Fig 3.** Heart Rate graph



**Fig 4.** ECG Signal graph

Fig 3 depicts heart rate patterns, Fig 4 illustrates ECG signal oscillations, and Fig 5 illustrates step count data, all of which provide further elaboration on the findings. By employing these graphs, the data can be more easily understood and the efficacy of the system can be better comprehended. In general, the outcomes indicate that field-programmable gate array (FPGA)-based intelligent health monitoring systems for ubiquitous devices could be of great assistance in delivering precise, real-time health monitoring.



**Fig 5.** Step Count of Individuals

## 5. Conclusion

Using field-programmable gate arrays (FPGAs) to construct ubiquitous smart health monitoring devices is a significant advancement when it comes to precise, real-time health tracking. These systems are well-suited for continuous monitoring as they combine cutting-edge sensors with the robust processing capabilities of FPGAs to deliver swift data analysis with minimal latency and decreased power consumption. The flexibility of the architecture ensures that when complex signal processing methods are implemented, they do so with high levels of data correctness and reliability. Furthermore, the power efficacy of the wearable devices is improved through the implementation of optimization strategies, which extends both the operational interval and battery life of the devices. This system outperforms conventional microcontroller-based state-of-the-art systems in terms of throughput, power efficiency, and performance. Through the exhibition of the revolutionary possibilities offered by field-programmable gate arrays (FPGAs), this novel methodology establishes a foundation for health monitoring systems that are both more advanced and intuitive for the average user. Further research and development will lead to enhanced practicality and wider integration of these systems into routine activities. Enhanced proactivity and individualized healthcare

administration ensue because of this.

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