Design of a Wireless Communication System for Wearable Device

by

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Conception d'un Système de Communication sans Fil pour Dispositif Portable

Alireza GHADERNAZARI

RÉSUMÉ

Cette recherche vise à concevoir, développer et évaluer un Dispositif Médical Souple Sans Fil (DMSF) pour améliorer les soins aux patients et la gestion des plaies. L'étude englobe une exploration multifacette des capacités du dispositif, de sa résilience et de ses applications pratiques dans le domaine de la technologie médicale.

La recherche aborde des sujets clés liés à la surveillance des plaies, à l'électronique souple, à la technologie des capteurs et aux soins de santé des patients. Elle examine l'impact de la température et de l'humidité sur la cicatrisation des plaies, explore la conception d'un boîtier prototype souple pour le DMSF et réalise des expériences pour évaluer les performances du dispositif dans des conditions environnementales variables.

Les hypothèses de travail tournent autour de l'adaptabilité du dispositif aux facteurs environnementaux, de sa résistance au stress et de ses capacités de synchronisation précise. Les méthodes de recherche comprennent des simulations expérimentales, des lectures d'oscilloscope, des tests de flexion et de déformation, ainsi qu'une analyse de tension des composants critiques tels que les cristaux RTC et oscillateurs.

L'étude démontre la résilience du DMSF face aux fluctuations de température et d'humidité, mettant en avant son adaptabilité à la surveillance des plaies. Elle présente la conception d'un boîtier prototype convivial et révèle la remarquable stabilité et la performance constante du dispositif en situation de stress physique. L'analyse des cristaux RTC et oscillateurs met en lumière leur rôle crucial dans la synchronisation précise et la collecte de données.

La recherche conclut que le DMSF souple offre un potentiel immense dans les applications de surveillance des plaies, en offrant une transmission précise des données et une durabilité dans des scénarios réels. Les recommandations incluent l'optimisation continue du dispositif pour une utilisation plus étendue dans le domaine de la santé et l'exploration de son potentiel dans d'autres domaines médicaux.

Mots-clés : Dispositif médical souple sans fil, surveillance de l'état des plaies, surveillance en temps réel, électronique souple, technologie médicale

Design of a Wireless Communication System for Wearable Device

Alireza GHADERNAZARI

ABSTRACT

This research aims to design, develop, and evaluate a Flexible Wireless Wearable Device (WWD) for enhanced patient care and wound management. The study encompasses a multifaceted exploration of the device's capabilities, resilience, and practical applications in the field of healthcare technology.

The research addresses key subjects related to wound monitoring, flexible electronics, sensor technology, and patient healthcare. It examines the impact of temperature and humidity on wound healing, explores the design of a flexible prototype case for WWD, and conducts experiments to assess device performance under varying environmental conditions.

The working hypotheses revolve around the device's adaptability to environmental factors, durability under stress, and precise timing capabilities. Research methods include experimental simulations, oscilloscope readings, bending and deforming tests, and voltage analysis of critical components such as RTC and oscillator crystals.

The study demonstrates the WWD's resilience to temperature and humidity fluctuations, emphasizing its adaptability for wound monitoring. It displays the design of a user-friendly prototype case and reveals the device's remarkable stability and consistent performance under physical stress. The analysis of RTC and oscillator crystals highlights their critical roles in precise timing and data synchronization.

The research concludes that the flexible WWD holds immense potential in wound monitoring applications, offering accurate data transmission and durability in real-world scenarios. Recommendations include further optimization of the device for broader healthcare use and exploration of its potential in other medical domains.

Keywords: Wireless wearable device, wound condition monitoring, real-time monitoring, flexible electronics, healthcare technology

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LIST OF ABBREVIATIONS AND ACRONYMS

AAR	Address Resolution
AC	Alternating Current
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
ARM	Advanced RISC Machines
BAT	Battery
BCN	Bayesian Convolution Network
BLE	Bluetooth Low Energy
CCM	Cryptographic Co-Processor Module
CHRG	Charge
CNN	Convolutional Neural Network
COVID-19	Coronavirus (SARS-CoV-2) 2019
CPU	Control Processor Unit
DC	Direct Current
DMA	Direct Memory Access
DSP	Digital Signal Processing
ECB	Electronic Code Book
ECG	Electrocardiogram
EXTI	Extended Interrupt/ Event Controller
FIFO	First In, First Out
GND	Ground

GPIO	General Purpose Input/Output
HSE	High-Speed External
HSI	High-Speed Internal
I/O	Input/Output
I^2C	Inter-Integrated Circuit
I_{BAT}	Charge Current
IC	Integrated Circuit
IoT	Internet of Things
IWDG	Independent Watchdog Timer
LDO	Low Drop-Out
LED	Light Emitting Diode
Li-ion	Lithium-ion
LPR	Low Power Run
MCU	Microcontroller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MR	Main Run
NRST	Negative Reset
PCB	Printed Circuit Board
PPG	Photoplethysmogram
PPI	Programmable Peripheral Interface
PROG	Program
RAM	Random Access Memory
RC	Reset and Clock Control

RH	Humidity
RISC	Reduced Instruction Set Computer
RNN	Recurrent Neural Networks
RSSI	Received Signal Strength Indicator
RTC	Real Time Clock
SMD	Surface Mount Device
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
TMP	Temperature
UART	Universal Asynchronous Receivers/Transmitters
ULP	Ultra Low Power
USART	Universal Synchronous/Asynchronous Receivers/Transmitters
USB	Universal Serial Bus
V_{CC}	Voltage at the Common Collector (Positive Input Supply Voltage)
V_{DD}	Voltage Direct Current (Supply Voltage)
V_{DDA}	Voltage Direct Current for Analog to Digital Converter
V_{REFINT}	Internal Voltage Reference
V_{SS}	Voltage Source Ground
WHO	World Health Organization
Wi-Fi	Wireless Fidelity
WKUP	Wake Up
WWD	Wireless Wearable Device

LIST OF SYMBOLS AND UNITS OF MEASUREMENT

Symbol	Measurement	Unit
°C	Celsius	Degree
μ (u)	Very small quantities (One millionth)	Micro-
A	Electrical current	Ampere
Byte (B)	Unit of data size	Byte
bit	Smallest unit of data	bit
bit/s	Data transmission speed	bit per second
dBm	Logarithmic unit	Min-decibels
F	Unit of capacitance	Farad
Hz	Frequency of electromagnetic waves	Hertz
K	Very big quantities (One thousands or 1024)	Kilo-
mAh	Electrical charge	Milliamper-hour
n	Very small quantities (One billionth)	Nano-
p	Very small quantities (Ten to power twelve)	Pico-
ppm	Deviation or variation from a reference value	Parts per million
V	Electrical voltage	Volt
W	Electrical power	Watts
Ω	Resistance	Ohm

INTRODUCTION

In recent years, wearable health technology has emerged as a promising field, offering innovative solutions for remote patient monitoring and healthcare management. This burgeoning field has sparked significant interest among researchers and healthcare professionals due to its potential to revolutionize the way we approach healthcare delivery. Among these advancements, the development of Wireless Wearable Devices (WWDs) stands out as a critical innovation aimed at improving wound care practices and patient outcomes.

The history of wearable devices dates back to the late 20th century, with the advent of rudimentary pedometers and heart rate monitors. However, recent advancements in materials science, sensor technology, and wireless communication have propelled wearable devices into the forefront of modern healthcare. These devices now possess the capability to continuously monitor various physiological parameters and have the potential to transform patient care.

Despite advancements in healthcare technology, current wound monitoring practices often rely on subjective assessments and periodic clinic visits, which can lead to delays in detection and treatment of wound complications. Moreover, existing wearable devices lack the flexibility, durability, and precision required for continuous and accurate wound assessment, particularly in dynamic real-world environments. Addressing these limitations is crucial for enhancing the quality of wound care and optimizing patient outcomes.

The primary objective of this thesis is to design, develop, and evaluate a novel WWD capable of providing continuous and real-time assessment of wound parameters in diverse clinical settings. Specifically, this research aims to:

- Design and fabricate a flexible and robust WWD capable of monitoring key wound parameters, including temperature and humidity, with disposable sensors, ensuring high precision and reliability.
- Conduct comprehensive experimentation and validation to assess the performance, durability, and accuracy of the developed WWD under simulated and real-world conditions.

To achieve the stated objectives, this research will address the following key research questions:

- What are the design requirements and specifications for developing a flexible and robust WWD?
- How does the developed WWD perform in terms of accuracy, durability, and reliability under simulated and real-world conditions?

The research will involve prototyping, experimentation, and validation of the WWD in simulated environments. However, certain limitations, such as resource constraints and regulatory considerations, may affect the scope and scale of the project.

The successful development and implementation of an effective WWD have the potential to significantly impact wound care practices and patient outcomes. By enabling continuous monitoring and early detection of wound complications, the WWD can facilitate timely interventions, reduce healthcare costs, and improve overall quality of life for patients. Additionally, the insights gained from this research can inform future advancements in wearable health technology and contribute to the broader field of healthcare innovation.

This thesis aims to contribute to the existing body of knowledge in wearable health technology and wound care by:

- Introducing a novel approach to continuous wound monitoring through the development of a flexible and robust WWD.
- Conducting comprehensive experimentation and validation to assess the performance, durability, and usability of the developed WWD in diverse clinical settings.

By addressing these aspects, this research seeks to advance the state-of-the-art in wearable health technology and contribute to improved patient care and healthcare outcomes.

CHAPTER 1

LITERATURE REVIEW AND RELATED RESEARCH

Wearable devices have gained significant attention in recent years due to their potential to revolutionize healthcare by enabling continuous monitoring of physiological parameters in a non-invasive and user-friendly manner. These devices, typically worn on the body or integrated into clothing or accessories, offer real-time collection, analysis, and feedback of data, empowering individuals to manage their health and well-being proactively. As the demand for personalized healthcare solutions continues to grow, the design and development of wearable devices have become an active area of research and innovation.

In the related work section of this thesis, we provide a comprehensive review of existing literature and research in the field of wearable devices to establish the current state-of-the-art, identify research gaps, and lay the foundation for the proposed design of a novel wearable device.

This section begins by presenting an overview of the different types of wearable devices that researchers have developed and their respective functionalities. It explores various physiological parameters that individuals can monitor, such as heart rate, blood pressure, temperature, respiratory rate, and activity level. Additionally, it delves into the technologies and sensors employed in these devices, including accelerometers, optical sensors, electrodes, and microfluidics, highlighting their strengths and limitations.

Then we review the design considerations and challenges associated with wearable devices. We explore factors such as comfort, ergonomics, power consumption, data accuracy, and data transmission. Furthermore, we study the integration of flexible WWDs with mobile applications to enable data analysis, visualization, and remote monitoring.

The related work section includes a review of the state-of-the-art algorithms and techniques utilized for data analysis and interpretation to provide a comprehensive understanding of the field. This includes applying machine learning, deep learning, signal processing, and pattern recognition methods to extract meaningful insights from the collected physiological data.

Moreover, it explores the use of data fusion techniques to enhance the accuracy and reliability of the captured information. This related work section aims to identify research gaps and opportunities for further advancement in wearable health device design by critically analyzing and synthesizing the existing literature. It sets the stage for the subsequent chapters of this thesis, which will propose a novel wearable health device design, integrating the knowledge gained from the related work analysis.

Several research papers have focused on the development of wearable health monitoring devices. (Taiyang Wu, Fan Wu, Chunkai Qiu, Jean-Michel Redouté & Mehmet Rasit Yuce, 2020), focus on the development of a wearable health monitoring sensor patch that combines rigid and flexible components. This sensor patch aims to provide continuous and accurate monitoring of various health parameters in Internet of Things (IoT)-connected healthcare applications. They emphasize the importance of wearable sensors in enabling remote healthcare monitoring and personalized medicine. They highlight the need for flexible and comfortable sensor patches that conform to the body's contours while ensuring reliable data acquisition. The proposed sensor patch consists of a rigid base housing electronic components, including sensors for measuring vital signs such as heart rate, body temperature, and respiration rate. Flexible interconnects enable comfortable wearability and robust electrical connections between the rigid components. They describe the fabrication process, involving the integration of rigid and flexible components using surface mounting technology and a flexible printed circuit board. They discuss the challenges faced in achieving flexibility, durability, and signal integrity in the design. They explore the wireless connectivity aspects of the sensor patch, enabling seamless data transmission to IoT platforms for real-time monitoring and analysis. They discuss the integration of Bluetooth Low Energy (BLE) technology to establish a reliable connection between the sensor patch and IoT devices. To validate the performance of the sensor patch, they conducted experimental tests involving human subjects. They evaluated the accuracy and reliability of the sensor measurements compared to reference devices and demonstrated the suitability of the patch for continuous health monitoring applications.

(In cheol Jeong, David Bychkov & Peter C. Searson, 2019), focus on the use of wearable devices in precision medicine and health state monitoring. They highlight their potential in providing personalized healthcare and facilitating real-time monitoring of various physiological parameters. They emphasize the importance of precision medicine, which tailors medical treatments and interventions to individual patients based on their unique characteristics and needs. Wearable devices play a crucial role in enabling personalized monitoring and data collection, leading to improved diagnostics, disease management, and healthcare outcomes. They explore different types of wearable devices used in precision medicine, including sensors, smartwatches, and fitness trackers. They discuss their capabilities and limitations in monitoring parameters such as heart rate, blood pressure, temperature, activity levels, and sleep patterns. They address the integration of wearable devices with data analysis and machine learning techniques, highlighting the significance of data processing algorithms in extracting meaningful insights. This integration enables early disease detection, personalized recommendations, and improved patient care. In addition, they discuss challenges related to wearable devices, such as data privacy, security, measurement accuracy, user compliance, and regulatory considerations. They stress the need for standardization, validation, and collaboration to ensure the reliability and effectiveness of wearable devices in precision medicine.

(Wei Jiang et al., 2022), focus on the development of a wearable telehealth system for monitoring Coronavirus (SARS-CoV-2) 2019 (COVID-19) and chronic diseases. They address the need for remote health monitoring solutions, particularly during the COVID-19 pandemic and for individuals with chronic diseases. The wearable telehealth system combines wearable devices, wireless communication, and data analysis techniques. Its objective is to provide continuous and real-time monitoring of vital signs, symptoms, and disease progression. They integrate wearable devices into the system, and these devices are capable of measuring physiological parameters such as body temperature, heart rate, respiratory rate, and oxygen saturation. These devices transmit the collected data wirelessly to a central monitoring unit. In addition, they discuss data analysis techniques, including machine-learning algorithms and artificial intelligence, used to analyze the collected data, detect anomalies, and provide predictive insights for timely intervention and personalized healthcare management. Moreover, they highlight the advantages of telehealth in providing remote monitoring and healthcare delivery, such as increased accessibility, reduced hospital visits, and early detection and prevention of complications.

(Nishant Verma et al., 2021), introduce a novel wearable device for continuous temperature monitoring and fever detection. They address the need for a convenient and accurate method to monitor body temperature, particularly in the context of fever, a common symptom of various illnesses. They design the wearable device to monitor temperature changes in real time. They incorporate sensors and wireless communication technology to collect temperature data and transmit it for analysis. The device's features include compact size, lightweight design, and a comfortable wearing experience. Its non-invasive nature allows for continuous temperature monitoring during daily activities. Moreover, they describe the fever detection algorithm employed in the device, which uses data analysis techniques to identify abnormal temperature patterns indicating the presence of a fever. Timely fever detection is crucial for early intervention and appropriate medical care. Experimental results demonstrate the accuracy and reliability of temperature measurements obtained from the wearable device compared to standard methods.

The development of low-power wearable systems for continuous monitoring of environmental and health factors, specifically for chronic respiratory diseases, is the focus of (James Dieffenderfer et al., 2016). They address the need for wearable devices capable of real-time monitoring of respiratory health and environmental factors affecting respiratory conditions. The wearable systems integrate sensors for monitoring respiratory parameters such as airflow, lung volume, and respiratory rate, along with sensors for environmental factors including temperature, humidity, and air quality. Low power consumption is crucial for long battery life and user comfort. They discuss techniques employed to minimize power consumption, such as optimizing sensor operation, data processing, and wireless communication. They employ data analysis techniques, including algorithms and signal processing methods, to extract meaningful information from the collected data. Experimental results validate the functionality and performance of the wearable systems, displaying their potential in monitoring respiratory parameters and environmental factors and identifying triggers and patterns related to respiratory conditions.

(Chike Nwibor et al., 2023), introduce a remote health monitoring system that aims to estimate blood pressure, heart rate, and blood oxygen saturation level. The system enables continuous non-invasive monitoring of these vital signs, facilitating remote healthcare and early detection of health issues. They discuss the design and implementation of the remote health monitoring system, which incorporates wearable sensors and wireless communication technology. These components collect and transmit real-time data on blood pressure, heart rate, and saturation level of blood oxygen to a remote monitoring center. Accurate estimation of these vital signs is crucial for effective health monitoring, and they elaborate on the signal processing techniques and algorithms employed in the system to extract meaningful information from the collected data and estimate the vital signs accurately. Furthermore, they address challenges related to remote health monitoring, including data transmission, privacy concerns, and the need for user-friendly interfaces. They propose solutions such as secure data transmission protocols and user-friendly mobile applications to overcome these challenges. Additionally, they present experimental results and validation of the remote health monitoring system, demonstrating its accuracy and reliability compared to standard measurement methods. Totally, this study discusses the potential applications of the system in remote healthcare, telemedicine, and early detection of health abnormalities.

(Zhiqing Zhou, Heng Yu & Hesheng Shi, 2020), focus on human activity recognition using a wearable IoT device to analyze healthcare data. They propos an improved Bayesian Convolution Network (BCN) algorithm for accurately recognizing and categorizing different human activities based on data collected from the wearable IoT device. They describe the architecture and functioning of the proposed BCN algorithm, which combines Bayesian techniques with Convolutional Neural Network (CNNs) to enhance activity recognition accuracy. The algorithm utilizes data captured by the wearable IoT device, such as motion patterns, biometric data, or sensor readings, to train the model and make predictions about the user's activities. Furthermore, they discuss the significance and potential applications of this research in the field of healthcare. Accurate activity recognition facilitated by the wearable IoT device could assist in monitoring patients' movements and behaviors, leading to better tracking of health conditions, activity levels, or adherence to prescribed treatments. This information holds value for personalized healthcare, rehabilitation, and remote patient monitoring.

(Ridwan Alam, David B. Peden & John C. Lach, 2021), focus on wearable devices for monitoring respiration and the development of interpretable inference methods using contextual information and sensor biomarkers. They discuss the challenges and advancements in wearable respiration monitoring technology and propose techniques to extract meaningful insights from the collected data. They address the design and functionality of wearable devices used for respiration monitoring, which includes sensors or electrodes placed on the body to capture respiratory signals and other relevant physiological data. They discuss the advantages and limitations of different sensor types for accurate respiration monitoring. In addition, they explore the concept of interpretable inference, which involves extracting actionable information and insights from the collected data, and emphasizes the importance of considering contextual information to enhance accuracy and relevance. They explore sensor biomarkers, which are specific measurements or patterns obtained from sensor data, as indicators of respiratory health or other relevant health conditions. They present methods and techniques for interpretable inference in wearable respiration monitoring, including algorithms or models that incorporate contextual information and sensor biomarkers to provide accurate interpretations of the collected data. In total, they discuss the potential applications and benefits of wearable respiration monitoring with interpretable inference, including aiding in the diagnosis, management, and monitoring of respiratory conditions, sleep disorders, or general wellness.

(Tianyiyi He & Chengkuo Lee, 2021), focus on the development and advancement of flexible sensors, wearable devices, and implantable technologies to create a comprehensive system called BodyNET. They aim to revolutionize healthcare and enhance quality of life by enabling advanced health monitoring and diagnostics. They discuss the evolution of flexible sensors, which can conform to the shape and movement of the human body, and their integration into wearable devices or implants. They explore various types of flexible sensors, such as biosensors, environmental sensors, or motion sensors. Wearable devices provide continuous monitoring of vital signs, physical activity, and other relevant health data, while implantable technologies offer even closer integration with bodily functions. They introduce BodyNET as an integrated system that combines flexible sensors, wearable devices, and implantable technologies to collect, analyze, and transmit health data for personalized healthcare management. They discuss the potential benefits of BodyNET, including early detection of health issues, remote patient monitoring, and personalized treatment plans. Additionally, they explore challenges and future directions in the field of evolving flexible sensors and wearable-implantable technologies.

(Mirto Musci, Daniele De Martini, Nicola Blago, Tullio Facchinetti & Marco Piastra, 2021), focus on the development and implementation of an online fall detection system using Recurrent Neural Network (RNNs) on smart wearable devices. They discuss the need for fall detection systems to assist individuals, particularly the elderly or those with mobility impairments, in timely fall detection and response. They address the limitations of existing fall detection methods, such as reliance on external sensors or continuous connectivity to a centralized monitoring system. The proposed solution involves using RNNs, suitable for sequential data analysis, to detect falls in real time on smart wearable devices. They describe the architecture and functioning of the RNN model, trained on labeled fall and non-fall data, to learn patterns and characteristics of falls. In addition, they discuss the data collection process and the specific sensor data used for fall detection, such as accelerometer and gyroscope readings from the wearable device. The collected sensor data is preprocessed and fed into the RNN model for online fall detection which the performance and evaluation of the fall detection system are presented, including metrics such as accuracy, sensitivity, and specificity.

(Sumit Majumder et al., 2018), focus on the development and application of noncontact wearable wireless ECG systems for long-term monitoring. They discuss the design, functionality, and potential benefits of these systems and address the limitations of traditional contact-based ECG systems, such as the need for skin preparation and electrode placement, and emphasize the advantages of noncontact ECG systems, which eliminate the need for direct skin contact and provide greater ease of use and mobility. They describe the design and components of noncontact wearable wireless ECG systems, which utilize techniques such as capacitive coupling or electromagnetic induction to detect and record the electrical activity of the heart. They discuss the technical details and considerations in developing such systems, including signal-processing algorithms, noise reduction techniques, and power management. They address the potential applications of noncontact wearable wireless ECG systems in long-term monitoring scenarios, such as continuous monitoring of cardiac activity in patients with cardiovascular conditions or health and wellness monitoring at home. They discuss the advantages of long-term monitoring in detecting and diagnosing cardiac abnormalities, assessing treatment effectiveness, and enabling early intervention. Besides, they discuss the challenges and future directions of noncontact wearable wireless ECG systems, including areas of improvement such as signal quality enhancement, motion artifact mitigation, power efficiency improvement, and ensuring data security and privacy.

(Simin Masihi et al., 2022), focus on the development of a flexible wireless ECG monitoring device for wearable applications. They discuss the design, fabrication, and performance of the device, which incorporates dry fabric electrodes for improved comfort and convenience and address the limitations of traditional ECG monitoring devices that use wet electrodes requiring gel or adhesive for skin contact. They emphasize the advantages of dry fabric electrodes, which eliminate the need for skin preparation, provide reliable ECG signals while maintaining user comfort, and describe the design and fabrication process of the flexible wireless ECG monitoring device, including the selection of materials, flexible substrate, dry fabric electrodes, and integration of electronic components. They address the challenges associated with achieving a compact and lightweight design suitable for wearable applications. They present the performance of the device, including the signal quality and accuracy of the ECG measurements obtained with the device. They discuss factors such as noise reduction techniques, power consumption, and wireless communication reliability. They discuss the potential applications and benefits of the flexible wireless ECG monitoring device for wearable healthcare, including continuous monitoring of cardiac activity, early detection of arrhythmias or other cardiac abnormalities, and remote patient monitoring. As well, they discuss the potential for integration with other wearable devices or health monitoring systems.

(Ahmad Rezaei, Mahta Khoshnam & Carlo Menon, 2021), focus on developing user-friendly wearable platforms for monitoring unconstrained indoor and outdoor activities. They discuss the challenges associated with current wearable systems and propose solutions to enhance user experience and activity monitoring accuracy. They address the limitations of existing wearable platforms such as discomfort, limited usability, and accuracy issues. They emphasize the need for user-friendly solutions that seamlessly integrate into users' daily lives and provide accurate and reliable activity monitoring data. They describe the design, sensor selection, and algorithms used to interpret sensor data and classify activities. The user-friendly aspect of the wearable platforms is a key focus of the paper, discussing considerations for comfortable and unobtrusive devices. Moreover, they discuss the evaluation of the platforms, including accuracy and user feedback. They explore potential applications and future directions, including integration with other healthcare systems and personalized activity monitoring.

(Andreas Tobola et al., 2018), focus on the development of a self-powered multi-parameter health sensor for wearable devices, aiming to continuously monitor various health parameters without relying on external power sources or frequent battery replacements. It highlights the limitations of traditional wearable sensors and emphasizes the importance of continuous monitoring of vital signs and other health parameters in healthcare and disease management. The research focuses on designing an energy-efficient sensor system, integrating multiple sensors for measuring heart rate, respiration rate, temperature, and activity level. Various energy harvesting techniques, such as solar energy or body heat, are explored to power the device, along with efficient energy management and storage systems. Results demonstrate the performance and reliability of the self-powered sensor, comparing favorably to traditional battery-powered sensors. The potential applications of the self-powered health sensor in remote or resource-constrained settings are discussed, suggesting integration into wearable systems or healthcare platforms to enable personalized health monitoring and telemedicine applications.

(Sarah Tonello et al., 2023), focus on the development and application of a novel aerosol jet printed flexible sensor for amperometric measurements, focusing on its integration into wearable devices for monitoring physiological parameters or detecting specific analyses. It highlights the increasing demand for wearable sensors in healthcare and other domains, emphasizing the need for flexible and customizable sensors that provide reliable real-time measurements. The fabrication process of the aerosol jet printed flexible sensor, including materials, printing techniques, and performance optimization, is described. Challenges associated with printing on flexible substrates and achieving high-quality sensor characteristics are addressed. Experimental results regarding sensitivity, selectivity, and stability are presented, comparing the sensor's performance to existing technologies. The integration of the sensor into wearable devices is discussed, along with its potential applications in healthcare monitoring, environmental sensing, and personalized diagnostics.

(Vishal Varun Tipparaju et al., 2020), focus on the development and implementation of a wearable mask device for reliable breathing tracking. The primary aim is to create a device capable of accurately monitoring respiratory parameters for healthcare, fitness, and wellness applications. Existing methods' challenges, such as discomfort and lack of accuracy, are highlighted, underscoring the need for a wearable solution. The design and functionality of the device, incorporating pressure, temperature, and gas sensors for accurate tracking, are described. Experimental results demonstrate the device's accuracy, sensitivity, and reliability in capturing respiratory parameters. Potential applications include monitoring respiratory conditions, detecting abnormalities, and assessing therapy efficacy. Integration into smart home systems, telemedicine platforms, and fitness tracking applications is explored. The significance of the wearable mask device for advancing respiratory monitoring technology and improving healthcare outcomes is emphasized, along with future development directions.

(Alexander Sun, A. G. Venkatesh & Drew A. Hall, 2016), focus on the development and implementation of a reconfigurable electrochemical biosensor, aiming to enable personal health monitoring using mobile devices. The research addresses the growing demand for portable and user-friendly biosensors for personal health monitoring, highlighting limitations of traditional biosensors and proposing reconfigurable electrochemical biosensors as a solution. The design integrates different sensing modalities onto a single platform, including amperometric, potentiometric, and impedance-based techniques. Experimental results demonstrate the biosensor's sensitivity, selectivity, and dynamic range for various analyses or biomarkers, enabling real-time monitoring of health parameters like glucose levels or pH using mobile devices. Integration with mobile devices includes data processing, communication capabilities, and mobile applications for interacting with the biosensor and visualizing acquired data. The benefits of the biosensor in personal health monitoring, point-of-care diagnostics, chronic disease management, and fitness tracking are discussed. Additionally, the reconfigurability of the biosensor is highlighted for adapting to different measurement needs and adding new sensing capabilities through software updates.

WWDs effectively bridge the divide between conventional healthcare practices and the contemporary need for continuous monitoring. By facilitating the collection of vital data, encompassing parameters like vital signs and physical activity, they equip users with the means to identify anomalies at their earliest stages. This early detection opens the door to proactive healthcare management, enabling timely interventions that mitigate potential issues. Moreover, user-friendly interfaces and ergonomic considerations ensure that individuals can effortlessly incorporate these devices into their routines, thereby fostering adoption and adherence.

One of the most remarkable facets of WWDs is their empowerment of individuals to manage their health actively. These devices afford users the ability to monitor crucial health metrics continuously, providing real-time data that can profoundly affect their overall well-being. Traditional healthcare, reliant on sporadic visits to medical practitioners, is yielding to this new paradigm where health monitoring is continuous and tailored to the individual.

Research in wearable health monitoring devices has advanced significantly in recent years, with various studies focusing on different aspects of development and application. As explained before (Taiyang Wu, Fan Wu, Chunkai Qiu, Jean-Michel Redouté & Mehmet Rasit Yuce, 2020), introduce a sensor patch combining rigid and flexible components for continuous health parameter monitoring, emphasizing the importance of wearability and reliable data acquisition. In contrast, (Wei Jiang et al., 2022) target remote health monitoring, particularly during the COVID-19 pandemic, integrating wearable devices with wireless communication and data analysis for real-time monitoring and personalized healthcare. Similarly, (Chike Nwibor et al., 2023) present a remote health monitoring system emphasizing accurate estimation of vital signs like blood pressure and heart rate, crucial for early detection of health issues.

Some researchers, such as (Zhiqing Zhou, Heng Yu & Hesheng Shi, 2020), delve into activity recognition using wearable IoT devices, offering potential applications in patient monitoring and rehabilitation. (James Dieffenderfer et al., 2016) focus on low-power wearable systems for chronic respiratory disease management, addressing the need for real-time monitoring of respiratory health and environmental factors affecting it. Similarly, (Ridwan Alam, David B. Peden & John C. Lach, 2021) discuss wearable devices for respiratory monitoring and the development of interpretable inference methods to extract actionable insights.

Other studies explore specific health parameters. For instance, (Nishant Verma et al., 2021) introduce a novel wearable device for continuous temperature monitoring and fever detection, crucial for early intervention and medical care. Meanwhile, (Sumit Majumder et al., 2018) focus on noncontact wearable wireless ECG systems, offering advantages in long-term monitoring for cardiovascular conditions.

Innovations like the flexible aerosol jet printed sensor (Sarah Tonello et al., 2023) and the reconfigurable electrochemical biosensor (Alexander Sun, A. G. Venkatesh & Drew A. Hall, 2016) push boundaries in sensor technology, paving the way for customizable and versatile solutions in healthcare monitoring.

The articles offer invaluable insights into the development and application of diverse wearable technologies across various domains. Upon a comprehensive examination of these articles, it is clear that WWDs are at the forefront of healthcare technology, addressing pressing challenges head-on. In an era characterized by the ever-increasing demands of the healthcare sector, wearable technologies have emerged as versatile and all-encompassing solutions to these multifaceted challenges. The significance of WWDs in healthcare is undeniable. They represent tools that actively empower individuals to participate in their health management, bridging the gap between traditional healthcare norms and the evolving needs of our times.

Several research papers focus on the development of wearable health monitoring devices that aim to provide continuous and accurate monitoring of various health parameters. These devices combine rigid and flexible components to ensure comfort and reliability while conforming to the body's contours. The integration of wearable devices with IoT platforms and telehealth systems enables remote monitoring and real-time data transmission for timely intervention and personalized healthcare management. These systems facilitate continuous monitoring of vital signs, symptoms, and disease progression.

Overall, while advancements in wearable health monitoring devices offer promising opportunities for personalized healthcare and remote monitoring, challenges such as accuracy and user compliance persist. Collaborative efforts towards standardization, validation, and user-centric design are essential for realizing the full potential of wearable health monitoring devices in improving healthcare outcomes.

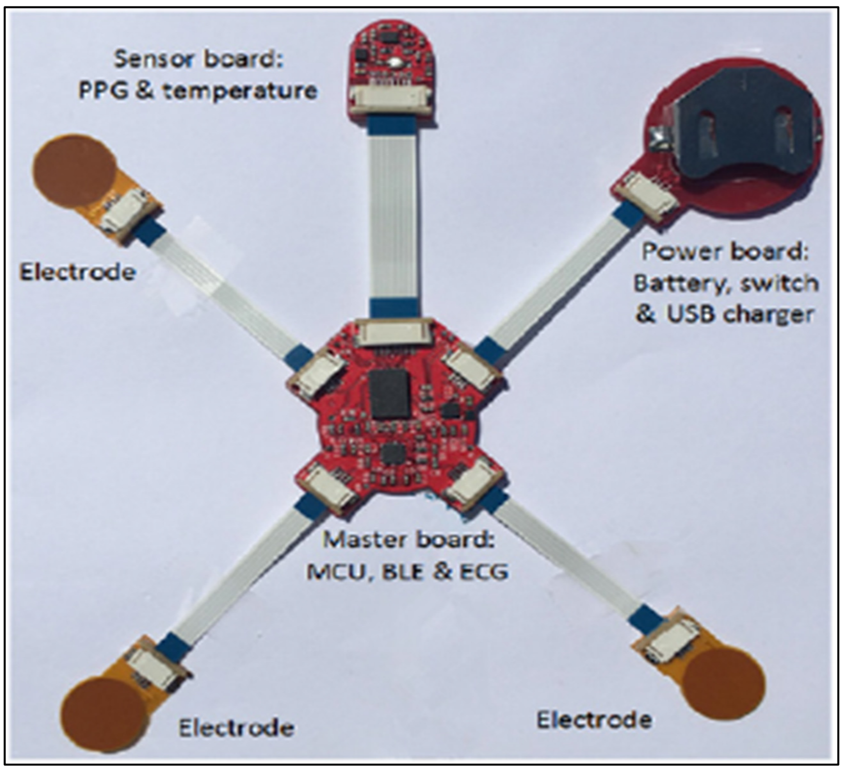

Figure 1.1 Rigid-flex design of the sensor patch for
health monitoring Taken from Taiyang Wu et al. (2020, p. 6934)

Upon reviewing the articles and examining the wearable devices, it becomes evident that few shortcomings are present among them. Typically, these devices incorporate non-disposable sensors with a rigid and intricate structure, thereby restricting flexibility and ease of use for patients. Figure 1.1 illustrates a wireless wearable device, showcasing a rigid-flex design of the sensor patch for health monitoring.

In this thesis, we aim to rectify these deficiencies by proposing the design and development of a WWD that is flexible and equipped with disposable sensors, alongside a user-friendly and practical casing.

In the next chapter, our focus lies in the creation and development of a WWD tailored to address specific healthcare needs. Our ultimate goal is to create a flexible, cost-effective, accessible, and user-friendly WWD designed to meet the demands of monitoring vital wound parameters. Our envisioned flexible WWD assumes the role of an empowering tool for patients recovering from surgical procedures. By concentrating on monitoring vital wound parameters such as temperature, humidity, etc. We aspire to empower patients with agency and control over their recovery process. This approach holds immense promise in early issue detection, enabling timely interventions and providing a more informed healthcare experience.

CHAPTER 2

METHODOLOGY AND DESIGN

This thesis focuses on designing and developing wireless wearable devices for health monitoring, specifically for wound monitoring. Identifying several key functional blocks is essential for designing a WWD based on essential aspects. Firstly, the power management block is crucial for ensuring long battery life and uninterrupted operation of the wearable device. The power management block includes ICs, energy harvesting components, and battery management systems to efficiently manage power consumption and rechargeable battery systems.

Secondly, the sensors block includes various sensors for monitoring vital signs like temperature, humidity, etc. We utilize temperature and humidity sensors for our wearable device, which have been developed and published by the lab of Professor Ricardo Izquierdo.

The next block is the wireless connectivity module, which facilitates communication between the wearable device and external devices such as smartphones, IoT platforms, or remote monitoring centers. It may incorporate BLE, Wi-Fi, or cellular connectivity for data transmission.

Lastly, the processing unit is responsible for collecting data from the sensors, performing data processing and analysis, and monitoring vital signs. It includes a Microcontroller Unit (MCU) as the primary component. Therefore, determining the appropriate type of MCU for designing the wearable device is essential. Various MCUs with different properties and options, such as the STM32 series, nRF51 series, ESP32, and Arduino boards, are available for use in health monitoring wearable devices.

All of these MCUs have low power consumption and support both analog and digital sensors. Additionally, they feature various interfaces such as Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI), and Universal Asynchronous Receivers/Transmitters (UART). These properties provide a wide range of options for selecting sensors.

These functional blocks work together to create a comprehensive WWD capable of continuous monitoring. The specific implementation and integration of these blocks may vary depending on the device's intended use case, target users, and technological requirements.

In this chapter, we will thoroughly examine the pros and cons of a variety of MCU options available for monitoring WWDs, to enhance our understanding of these choices. This crucial initial step will serve as a foundation for our subsequent discussions to elucidate why we selected the STM32 series for the prototype version and the nRF51 series for the ultimate version of MCUs in the design of our flexible WWD. Following that, we will delve into the key features of each type of MCU.

We aim to provide clarity regarding why we consider the STM32 and nRF51 series to be the optimal choices for our specific application by gaining an understanding of the strengths and potential limitations of each.

This comprehensive exploration, supported by robust scientific methods, will provide us with a solid foundation for the subsequent sections. We will subsequently delve into the technical intricacies of the selected MCUs. Furthermore, we will elucidate the design process for both the prototype and ultimate flexible WWDs, along with their respective components. We will also detail how these components interconnect and function together, facilitating a comprehensive understanding of the entire system. This in-depth examination will enable us to grasp the essential technology underpinning advanced health monitoring wearables.

2.1 Microcontroller Unit (MCU) Overview

The MCU plays a crucial role in the development of a WWD. When choosing an MCU for a WWD designed for monitoring wound parameters such as temperature and humidity, one must consider several factors. These factors include processing power, energy efficiency, communication capabilities, and the development environment. While the choice of the best MCU ultimately depends on the specific requirements and constraints of the project, there are several commonly used MCUs for WWDs:

- *STM32 series*

  The STM32 MCUs from STMicroelectronics offer a wide range of options suitable for WWDs. They strike a balance between performance, power efficiency, and a robust development ecosystem. For instance, wearable applications commonly employ the STM32F4 or STM32L4 series MCUs because of their low power consumption and extensive peripheral support.

- *nRF51 series*

  Nordic Semiconductor produces the nRF51 series of MCUs, specifically designed for low-power wireless applications, much like their nRF52 counterparts. They are equipped with BLE capabilities, making them particularly well suited for use in WWDs. Among the nRF51 series, models such as the nRF51822 and nRF51824 have gained popularity due to their focus on power efficiency, advanced features, and robust support for BLE connectivity. They facilitate the creation of energy-efficient wearable health monitoring devices, harnessing the benefits of BLE technology to ensure seamless communication while preserving battery life.

- *ESP32*

  Espressif Systems is known for designing the ESP32 MCU, which features integrated Wireless Fidelity (Wi-Fi) and Bluetooth capabilities. It offers ample processing power, low power consumption, and a rich set of features for wearable applications. The built-in Wi-Fi can be advantageous if you desire remote monitoring or cloud connectivity.

- *Arduino boards*

  Arduino boards, such as Arduino Nano or Arduino Pro Mini, provide a straightforward and beginner-friendly platform for WWD development. Although they may have lower processing power compared to other MCUs, they offer ease of use, a large community, and a wide range of compatible sensors and modules.

Engaging in a comprehensive assessment of the technical specifications and functionalities of various MCUs will help us identify the most suitable option for our WWD.

We can compare the four categories of microcontrollers commonly used in WWDs for wound monitoring (STM32 series, nRF51 series, ESP32, and Arduino boards) and discuss their advantages and disadvantages:

- *STM32 Series*
  - Advantages:
    - Wide range of MCUs with varying capabilities and features.
    - Strong development ecosystem with extensive documentation, libraries, and community support.
    - Good balance between performance and power efficiency.
    - Robust peripheral support for sensor integration and communication protocols.
  - Disadvantages:
    - Requires more advanced programming knowledge compared to beginner-friendly platforms like Arduino.
    - Higher cost compared to some other options.
    - Limited built-in wireless connectivity compared to specialized wireless MCUs.
- *nRF51 Series*
  - Advantages:
    - Built-in BLE capabilities make them ideal for WWDs.
    - Low power consumption, extending battery life for wearable applications.
    - Good support for BLE connectivity and protocols.
    - Offers a range of MCUs with varying memory and processing capabilities.
  - Disadvantages:
    - Limited wireless connectivity options compared to MCUs with integrated Wi-Fi.

- ➢ Development ecosystem may not be as extensive as more widely used MCUs like STM32.
- ➢ Limited availability of peripheral options compared to more established MCUs.

- *ESP32*
  - Advantages:
    - ➢ Integrated Wi-Fi and Bluetooth capabilities for wireless connectivity.
    - ➢ Lower cost compared to some other options.
    - ➢ Good processing power for a wide range of applications.
    - ➢ Large community and extensive documentation available.
  - Disadvantages:
    - ➢ Higher power consumption compared to specialized low-power MCUs.
    - ➢ Limited analog input channels, which may be a drawback when interfacing with analog sensors.
    - ➢ May not offer as many advanced peripheral features as some other MCUs.

- *Arduino Boards*
  - Advantages:
    - ➢ Beginner-friendly platform with a simple programming environment and extensive documentation.
    - ➢ Lower cost compared to some other options.
    - ➢ Large community support and a wide range of compatible sensors and modules.
    - ➢ Wide availability of development boards and shields.
  - Disadvantages:
    - ➢ Limited processing power and memory compared to more advanced MCUs.

- Limited built-in wireless connectivity options, requiring additional modules for wireless communication.
- Less suited for complex applications with demanding computational requirements.

It is crucial to consider the unique requirements and constraints of our WWD when choosing an MCU. We should carefully evaluate aspects such as power consumption, processing capabilities, wireless connectivity, development support, and cost. This analysis will enable us to identify the most suitable MCU for our WWD, specifically designed for wound monitoring.

When assessing four MCU classifications (STM32 series, nRF51 series, ESP32, and Arduino boards) for creating a WWD focused on monitoring vital wound parameters, the STM32F030F4P6 stands out as an apt prototype model due to several compelling factors:

- *Processing Power*

  This MCU, part of the STM32 series, offers sufficient processing power for data acquisition, sensor interfacing, and algorithm implementation.

- *Power Efficiency*

  Designers created this MCU with low power consumption in mind, making it suitable for battery-powered WWDs. Its low-power modes, efficient clock management, and optimized peripherals help minimize power consumption, thereby extending the battery life.

- *Communication Capabilities*

  While all the mentioned MCUs support wireless communication, integrating this MCU with the HC-05 BLE module allows for seamless BLE connectivity. BLE is widely used in WWDs due to its low power consumption, compatibility with smartphones, and ease of implementation.

- *Development Ecosystem*

  The STM32 MCUs have a well-established and mature development ecosystem. Various development tools and libraries are available, including the STM32 Cube platform, which provides a comprehensive set of software libraries, middleware, and examples to simplify application development. The availability of documentation, community support, and online resources further facilitate the prototyping process.

Considering these factors, the STM32F030F4P6 MCU presents itself as a fitting selection for a prototype model of a WWD designed for wound monitoring. Its harmonious combination of processing power, energy efficiency, communication capabilities especially when coupled with the HC-05 BLE module, and a resilient development ecosystem positions it as an optimal platform for initial testing and validation of the device concept.

On the other hand, it may become necessary to conduct additional assessments and fine-tuning to choose the most appropriate MCU for the ultimate flexible WWD. Factors such as cost, flexibility, scalability, and specific application requirements will influence this decision.

Let us examine several key factors to compare the four categories of MCUs (STM32, nRF51, ESP32, and Arduino) and determine why the nRF51822 is more suitable as a flexible device for the ultimate design of a WWD for wound monitoring:

- *Processing Power*

  The nRF51 series, including the nRF51822, offers sufficient processing power for most wearable applications. While the STM32 and ESP32 MCUs also provide good processing capabilities, the nRF51 series stands out with its efficient Cortex-M4 core, enabling advanced data processing and algorithm implementation.

- *Power Efficiency*

  Especially designed for low-power applications, the nRF51822 is an excellent choice for WWDs. Its power optimization features, such as low-power modes and configurable sleep timers, contribute to a longer battery life. The ESP32 and STM32 MCUs also offer power-efficient options, but the nRF51 series excels in this area.

- *Wireless Connectivity*

  The nRF51822 MCU integrates BLE capabilities, which are highly suitable for WWDs that require wireless communication with smartphones or other devices. BLE provides low-power consumption and reliable data transmission. While the ESP32 also offers integrated Wi-Fi and Bluetooth, the nRF51 series focuses on optimized BLE connectivity, making it the preferred choice for power-constrained wearable applications.

- *Flexibility and Form Factor*

  The nRF51822 MCU is available in a compact and flexible form factor, making it well suited for WWDs. Its small package size and compatibility with flexible Printed Circuit Board (PCB) designs allow for integration into various form factors, including wearable patches, wristbands, or smart clothing. The flexibility and size advantages of the nRF51822 make it a desirable choice for wearable applications where space and form factor constraints are crucial.

Taking into account these considerations, the nRF51822 MCU emerges as a superb choice for the ultimate design of a flexible WWD dedicated to wound monitoring.

Its blend of processing capability, power efficiency, built-in BLE connectivity, and adaptability in terms of form factor, position it as an ideal option to fulfill the precise demands of a WWD. It enables dependable wireless communication, facilitates efficient data processing, and offers versatility in design and integration, making it highly suitable for a flexible wearable solution.

2.2 Designing the Prototype WWD Using the STM32 MCU

The Altium Designer software (Version 21.6.4) is a sophisticated tool used for creating electrical circuit designs, including those for WWDs. In the initial stage, we employ the STM32F030F4P6 MCU as the primary MCU for the Prototype WWD. Subsequently, we choose additional components based on the recommendations provided in the MCU's datasheet and our requirements.

The MCU under discussion incorporates the latest generation of ARM® Cortex®-M0 processors, specifically designed for embedded systems. Developed to offer an affordable platform that provides to the requirements of MCU implementation, this particular MCU features a reduced pin count and low power consumption. Despite its efficient resource utilization, it delivers impressive computational performance and exhibits advanced system responsiveness to interrupts (STMicroelectronics NV, 2021).

2.2.1 Power Supply Features of the STM32 MCU

- Voltage Direct Current (V_{DD}) = 2.4 to 3.6V
  External power supply for Input/Output (I/Os) and the internal regulator. Provided externally through V_{DD} pins (STMicroelectronics NV, 2021).

- Voltage Direct Current for ADC (V_{DDA}) = from V_{DD} to 3.6V
  External analog power supply for Analog-to-Digital Converter (ADC), Reset blocks, Reset and Clock Control (RCs) (STMicroelectronics NV, 2021).

2.2.2 Voltage Regulation for the STM32 MCU

The regulator has two operating modes and it is always enabled after reset (STMicroelectronics NV, 2021).

- Main Run (MR) is used in normal operating mode (Run).
- Low Power Run (LPR) can be used in Stop mode where the power demand is reduced.

It supports three LPR modes to achieve the best compromise between low power consumption, short startup time, and available wakeup sources (STMicroelectronics NV, 2021):

- **Sleep mode,** in sleep mode, only the CPU is stopped. All peripherals continue to operate and can wake up the CPU when an interrupt/event occurs.

- **Stop mode** achieves very low power consumption while retaining the contents of SRAM and registers. All clocks in the 1.8V domain are stopped; The High-Speed

Internal (HSI) RC, and the High-Speed External (HSE) crystal oscillators are disabled. The voltage regulator can be set to either normal or low-power mode.

- **Standby mode,** the Standby mode is used to achieve the lowest power consumption. Switching off the internal voltage regulator powers down the entire 1.8V domain. The HSI RC, and the HSE crystal oscillators are switched off. Upon entering Standby mode, SRAM and register contents are lost, except for registers in the RTC domain and Standby circuitry. The device exits Standby mode when triggered by an external reset via the Negative Reset (NRST) pin, an Independent Watchdog Timer (IWDG) reset, a rising edge on the Wake-Up (WKUP) pins, or an RTC event.

In Standby mode, the MCU enters a power-down state. In this mode, the regulator output is in high impedance, and the core circuitry is powered down, resulting in zero consumption although the contents of the registers and SRAM are lost (STMicroelectronics NV, 2021).

2.2.3 Analog-to-Digital Converter (ADC) for the STM32 MCU

The ADC featured in this MCU possesses a 12-bit resolution and supports a maximum of 16 external channels, along with two internal channels designated for temperature sensing and voltage reference measurement. It conducts conversions in either single-shot mode or scan mode.

In scan mode, the ADC automatically performs conversions on a predetermined group of analog inputs. Additionally, the ADC can be utilized in conjunction with a Direct Memory Access (DMA) controller for improved efficiency. A notable capability of this ADC is the analog watchdog feature, which enables precise monitoring of the converted voltage on one or multiple selected channels. Whenever the converted voltage falls outside the programmed threshold values, an interrupt is generated, alerting the system to this occurrence (STMicroelectronics NV, 2021).

2.2.4 Internal Voltage Reference (V_{REFINT}) for the STM32 MCU

The ADC benefits from a V_{REFINT}, which generates a stable voltage output using a bandgap technique. V_{REFINT} is internally linked to the ADC_IN17 input channel. During the Production test, ST measures the exact voltage of V_{REFINT} for each individual component and saves this information in the system memory. This stored value can be accessed in a Read-Only mode, allowing for accurate reference voltage measurement during ADC operations (Table 2.1) (STMicroelectronics NV, 2021).

Table 2.1 Internal voltage reference calibration values
Taken from STMicroelectronics NV (2021, p. 18)

Calibration Value Name	Description	Memory address
V_{REFINT_CAL}	Raw data acquired at a temperature of 30°C (± 5 °C), V_{DDA}= 3.3V (± 10mV)	0x1FFF F7BA - 0x1FFF F7BB

2.2.5 Universal Synchronous/Asynchronous Receiver/Transmitter (USART) for the STM32 MCU

The MCU embeds up to six USART that communicate at speeds of up to six Mbit/s. Table 2.2 presents more details of the USART. (STMicroelectronics NV, 2021):

Table 2.2 USART implementation
Adapted from STMicroelectronics NV (2021, p. 23)

USART modes/ features	USART
Multiprocessor communication	Supported
Synchronous mode	Supported
Single-wire Half-duplex communication	Supported
Receiver timeout interrupt	Supported
Auto baud rate detection	Supported
Driver enable	Supported
USART data length	8 and 9 bits

A TSSOP20 package represents the pin configuration of the STM32F030F4P6 MCU used in the design of the Prototype WWD. Figure 2.1 depicts this package, consisting of 20 pins. (STMicroelectronics NV, 2021).

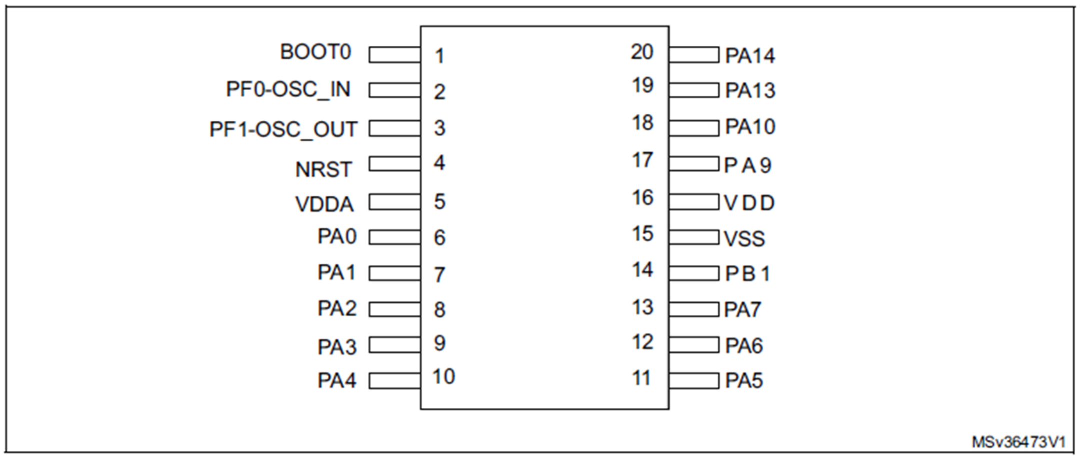

Figure 2.1 TSSOP20 20-pin package pinout (top view)
Taken from STMicroelectronics NV (2021, p. 27)

The STM32F030F4P6 MCU offers an economical price point while providing a sufficient number of analog inputs for sensor integration. As stated in its datasheet, it features up to nine channels with a 12-bit ADC, offering a resolution of 4096 discrete levels. This high resolution is beneficial for accurately measuring analog data captured by the sensors (STMicroelectronics NV, 2021).

Additionally, we have chosen the TSSOP20 package for its simplicity and cost-effectiveness in terms of design and assembly. Furthermore, the MCU supports the USART protocol, making it compatible with common interfaces and enabling seamless connection to the HC-05 BLE module, which facilitates data transmission to devices such as smartphones (STMicroelectronics NV, 2021). Refer to Table 2.3 for additional crucial details.

Table 2.3 STM32F030F4 features and peripheral counts
Adapted from STMicroelectronics NV (2021, p. 10)

Peripheral		STM32F030F4
Flash (Kbytes)		16
SRAM (Kbytes)		4
Timers	Advanced control	1 (16-bit)
	General purpose	4 (16-bit)
Comm. interfaces	Serial Peripheral Interface (SPI)	1
	Inter-Integrated Circuit (I^2C)	1
	USART	1
12-bit ADC (number of channels)		1 (9 ext. +2 int.)
General Purpose Input/Output (GPIOs)		15
Max. CPU frequency		48 MHz
Operating voltage		2.4 to 3.6 V
Operating temperature		Ambient operating temperature: -40°C to 85°C Junction temperature: -40°C to 105°C
Packages		TSSOP20

2.3 Schematic Design of the Prototype WWD with the STM32F030F4P6 MCU

Based on the features of the MCU, we have designed a schematic for the Prototype WWD, as depicted in Figure 2.2. In the subsequent section, we elucidate the specifics of each block and component employed in the design.

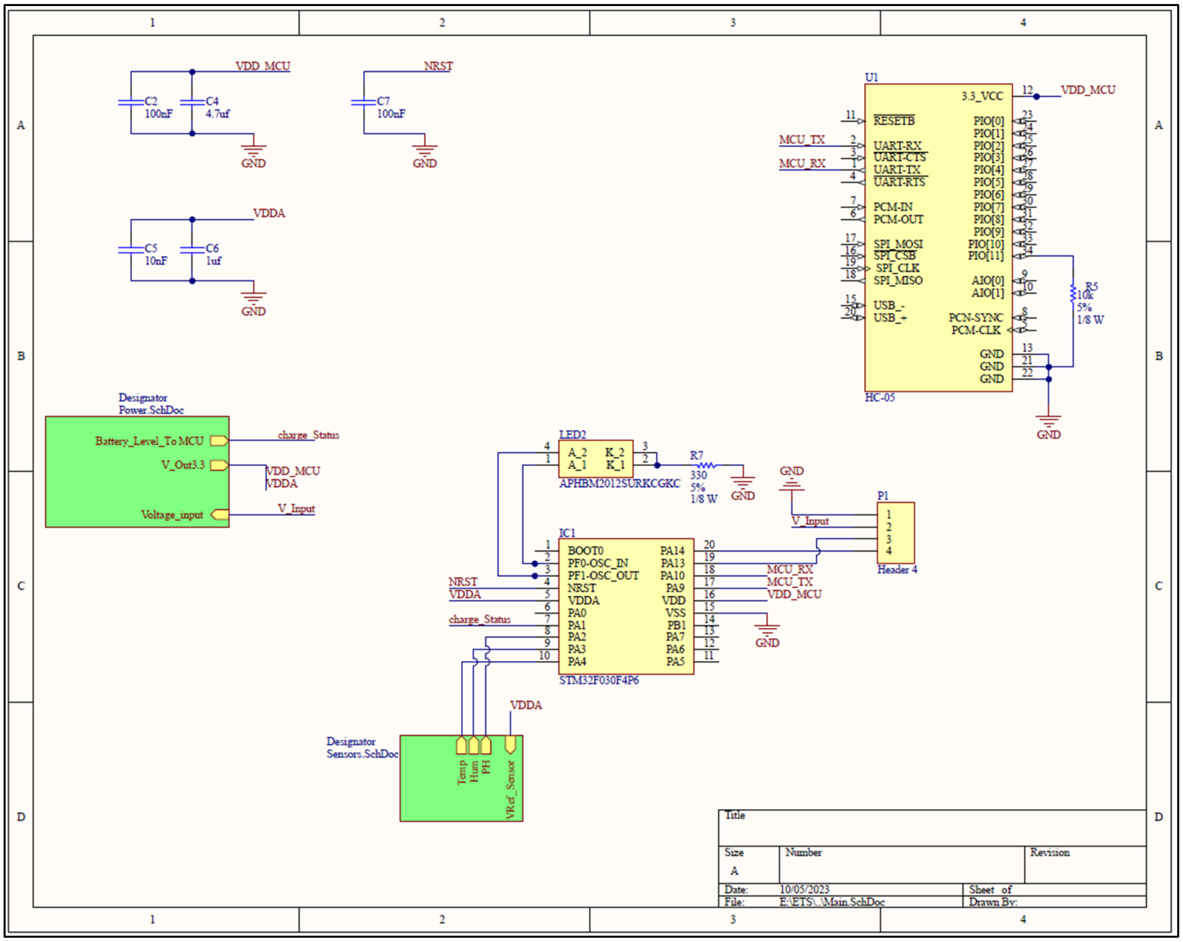

Figure 2.2 Schematic Design of the Prototype WWD with the STM32F030F4P6 MCU

2.3.1 Schematic Design of Light Emitting Diode (LED)

To set up the Prototype WWD, it is necessary to configure the connections based on our design requirements. In our design, we have a dual LED that should be connected to digital pins PF0 (Pin2) and PF1 (Pin3), as shown in schematic Figure 2.3. Although there are other pins, such as PB1 (Pin14), that can be utilized as digital pins, it is preferable to use Pin2 and Pin3 to minimize the distance between the MCU and the LED. This choice helps create a more compact design for the Prototype WWD.

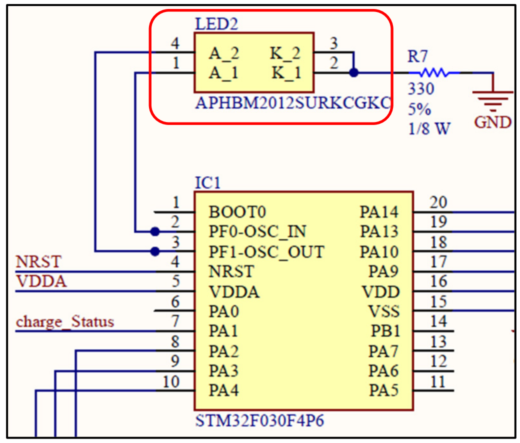

Figure 2.3 Schematic design for LED

The Prototype WWD utilizes an LED known for its minimal power consumption and compact size, providing a wide viewing angle in red and green color. It serves the purpose of conveying important information to the user, such as the battery status or the operational mode of the wearable. We can program the LED to convey various pieces of information by employing different flashing patterns. It is specifically recommended for implementation in WWDs, portable devices, and healthcare applications (Kingbright, 2020).

In the design of the Prototype WWD, the MCU supplies a voltage of 3.3V to pins 2 and 3, which are connected to the LED. Consequently, it is necessary to connect a 330Ω resistor in series with the LED to achieve a current of 10mA for the LED.

2.3.2 Schematic Design of Negative Reset pin (NRST)

The NRST (Pin4) is typically used for external reset control or for initiating a reset of the MCU. The MCU incorporates an NRST that serves the purpose of resetting the MCU. It is connected to a pull-up resistor that ensures a consistent high state.

It is possible to replicate common failures, such as unexpected resets and program counter corruption by manually forcing the NRST or the Oscillator pins to a low state for a duration of one second (STMicroelectronics NV, 2021).

It is advisable to refer to Figure 2.4 in the MCU's datasheet to utilize the NRST effectively, as it provides a recommended schematic for using the NRST. (STMicroelectronics NV, 2021).

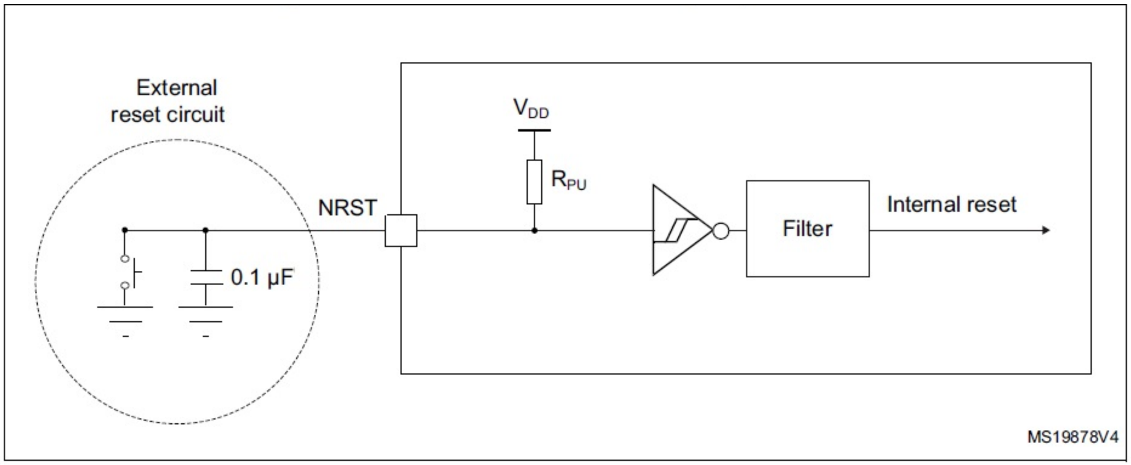

Figure 2.4 Recommended schematic for NRST
Adapted from STMicroelectronics NV (2021, p. 67)

In the design of the Prototype WWD, we opted to exclude the relatively large push button recommended in Figure 2.4 of the datasheet. We make this decision with the aim of creating a small and flexible Prototype WWD with reduced complexity.

Instead, as per the datasheet's recommendation, we need a 0.1μF capacitor to prevent any unintended activation of the NRST (Figure 2.5).

This external capacitor acts as a protective measure against parasitic resets. It is crucial to position the capacitor as close as possible to the NRST to maximize its effectiveness in preventing unwanted activation.

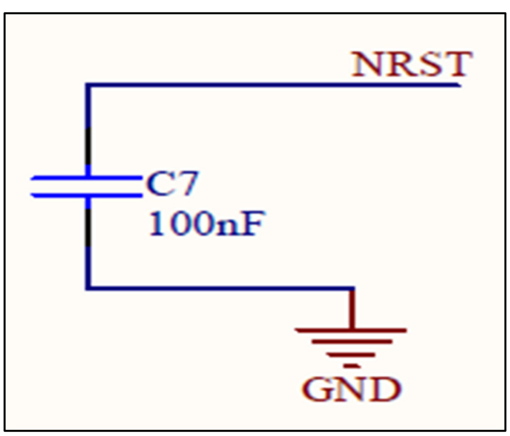

Figure 2.5 Schematic design for NRST

2.3.3 Schematic Design of Voltage Domain for ADC (V_{DDA})

The V_{DDA} (Pin5) supplies power to the ADC circuitry within the MCU, ensuring accurate processing of analog signals.

The MCU includes an internal circuit for V_{DDA}, providing a voltage of 3.3V specifically for the analog components and blocks.

The manufacturer provides a recommended schematic for the power supply block in the datasheet, available in Figure 2.6.

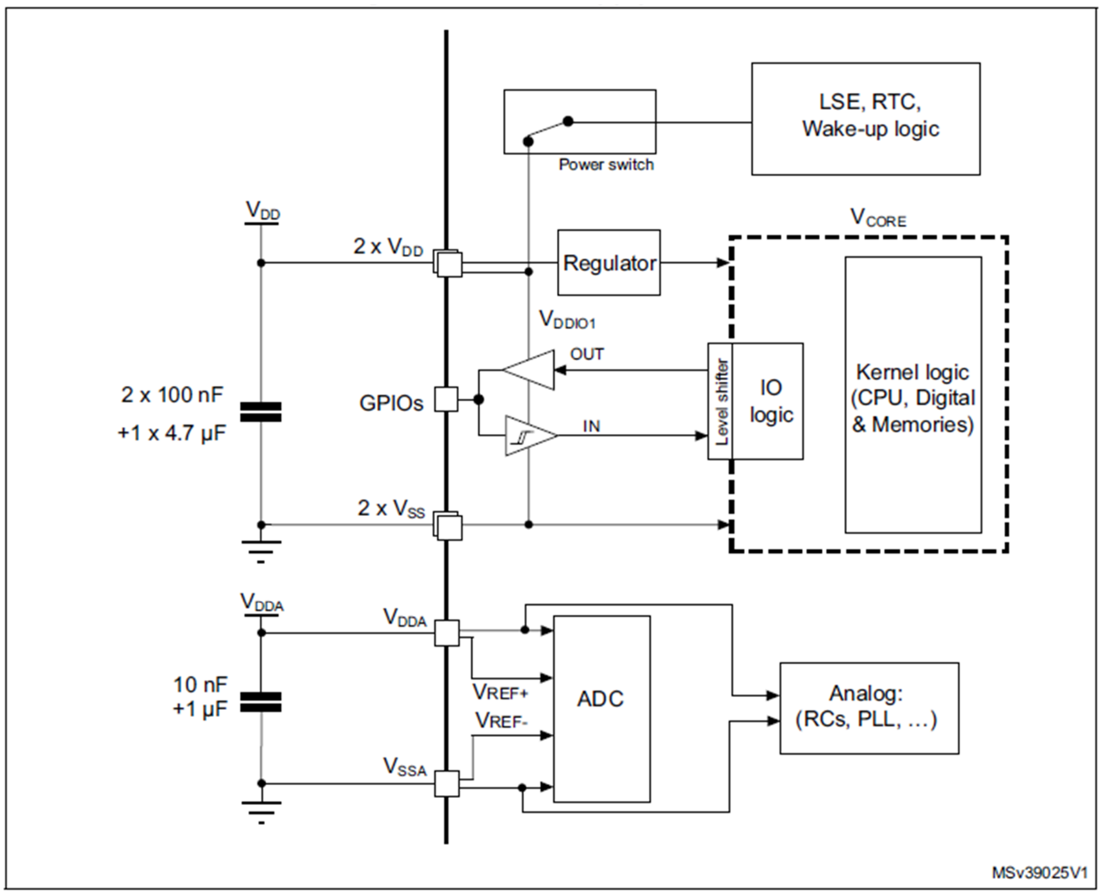

Figure 2.6 Power supply scheme
Taken from STMicroelectronics NV (2021, p. 42)

In the schematic design shown in Figure 2.7, it is crucial to place the capacitors in close proximity to the V_{DDA}. This positioning serves the purpose of safeguarding the V_{DDA} against potential interference, parasites, and resonance.

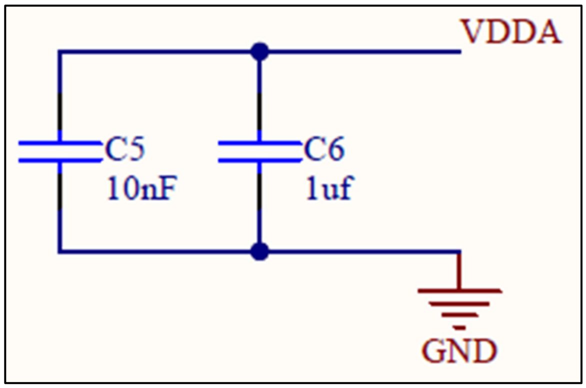

Figure 2.7 Schematic design for V_{DDA}

2.3.4 Schematic Design of Analog-to-Digital Convertor (ADC)

We use the ADC pins (Pin7, Pin8, Pin9, and Pin10) to connect analog signals to the MCU for conversion into digital values. Specifically, the PA1 (Pin7) functions as an indicator for the battery charge status in the WWD (Table 2.4). It operates by receiving an input analog voltage from the Charge Integrated Circuit (IC).

For instance, we can use this pin to activate the Green LED when the battery is fully charged or the Red LED when the battery level drops to approximately 20%. We can configure these various modes within the MCU.

As the sensors used in this Prototype WWD are analog in nature, we need to use the MCU's ADC to convert the analog sensor voltages into digital signals. The ADC functionality is assigned to three pins, namely PA2 (Pin8), PA3 (Pin9), and PA4 (Pin10) (Table 2.4).

It is worth noting that while the datasheet provides instructions for a standard sensor circuit, the sensors used in this particular Prototype WWD deviate from the standard design.

Table 2.4 Base configuration function

Pin Number	Pin Name	Channel	Function
7	PA1	IN1	Charger status
8	PA2	IN2	pH sensor (Reserved)
9	PA3	IN3	Humidity sensor
10	PA4	IN4	Temperature sensor

The MCU dedicates pins 7 through 10 to analog-to-digital voltage input, corresponding to channels one through four. We can configure the MCU's base settings using the software STM32CubeMX.

Figure 2.8 presents the initial configuration parameters for these bases, which can be adjusted according to the desired conditions.

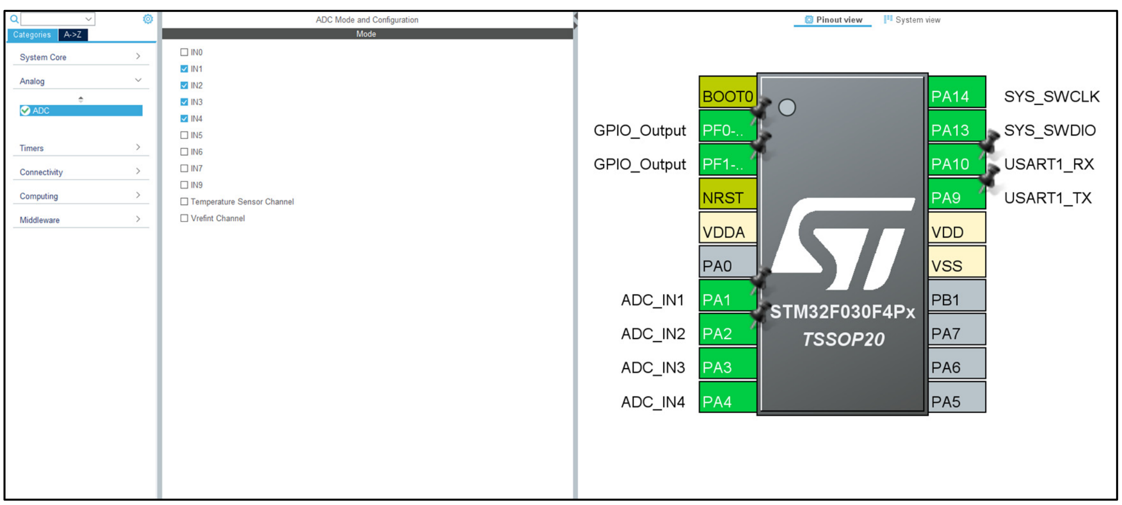

Figure 2.8 MCU base configuration
Taken from STM32CubeMX (2023, v. 6.9.2)

Table 2.5 highlights several additional features of the device. We configure the clock pre-scaler to operate in an asynchronous mode. Additionally, we set the ADC to a resolution of 12 bits, and the sampling time is established at 1.5 cycles. The manufacturer initially recommends these values, but they can be adjusted to accommodate preferred modes or specific requirements.

Table 2.5 Configuration of ADC pins in STM32CubeMX

ADC Settings	Clock Prescaler	Asynchronous clock mode
	Resolution	ADC 12-bit resolution
	Data Alignment	Right alignment
	Scan Conversion Mode	Forward
	Continuous Conversion Mode	Disabled
	Discontinuous Conversion Mode	Disabled
	End Of Conversion Selection	End of single conversion
	Overrun Behaviour	Overrun data preserved
	Low Power Auto Wait	Disabled
	Low Power Auto Power Off	Disabled
ADC Regular Conversion Mode	Sampling Time	1.5 Cycles
	External Trigger Conversion Source	Regular conversion launched by software

2.3.5 Schematic Design of Debug Serial Wire

The following two pins on the MCU, namely PA13 (Pin19) and PA14 (Pin20), connect to pins 3 and 4 of a header labeled as "Header 4", as illustrated in Figure 2.9. These pins serve as the debug serial wire and are used for both debugging and programming the MCU. The header also includes two additional pins: the first one functions as the common Ground (GND), while the second one acts as the power input (V_Input).

During the debugging and programming process, it is necessary for the MCU to share the same ground as the debugger adaptor. Therefore, we designate the first pin of the header as the common ground. Additionally, The debugger adaptor can provide 3.3V to power the MCU during debugging, making the second pin function as V_Input (VDD) (refer to Figure 2.9).

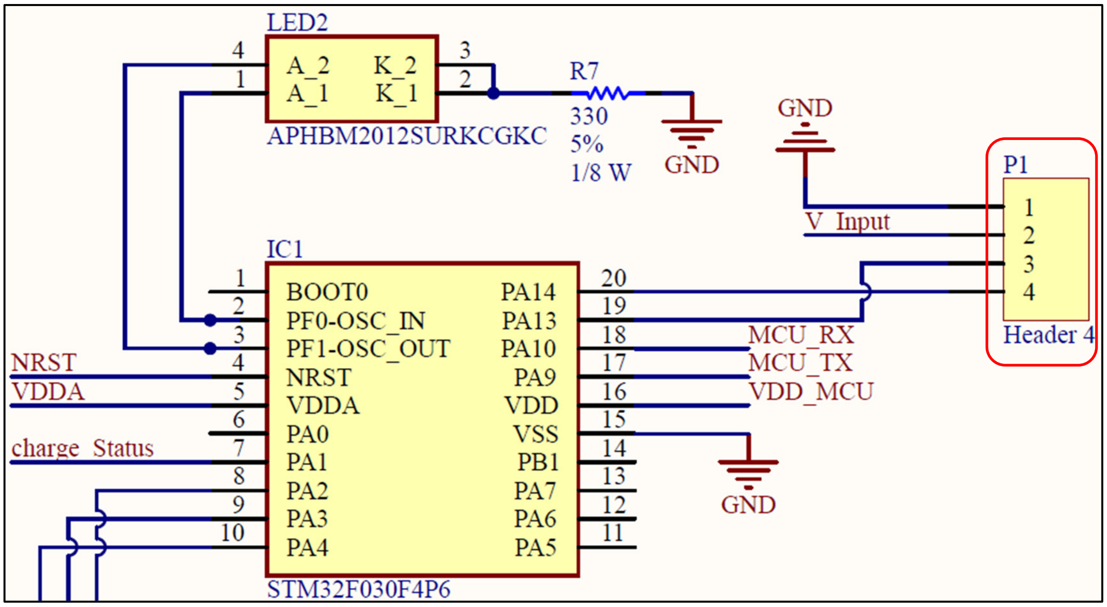

Figure 2.9 Schematic design for pin header connection

Figure 2.10 illustrates the ST-LINK V2 debug adaptor for both debugging and programming the MCU.

Figure 2.10 Debug adaptor ST-LINK V2

2.3.6 Schematic Design of Universal Synchronous/ Asynchronous Receiver/ Transmitter (USART)

USART is a versatile communication interface used for serial communication, supporting both synchronous and asynchronous communication modes for programming the MCU. As shown in schematic Figure 2.11, the MCU's PA9 (Pin17) (USART1_TX) and PA10 (Pin18)

(USART1_RX) pins are connected to the HC-05 module's pin2 (USART_RX) and pin1 (USART_TX), respectively.

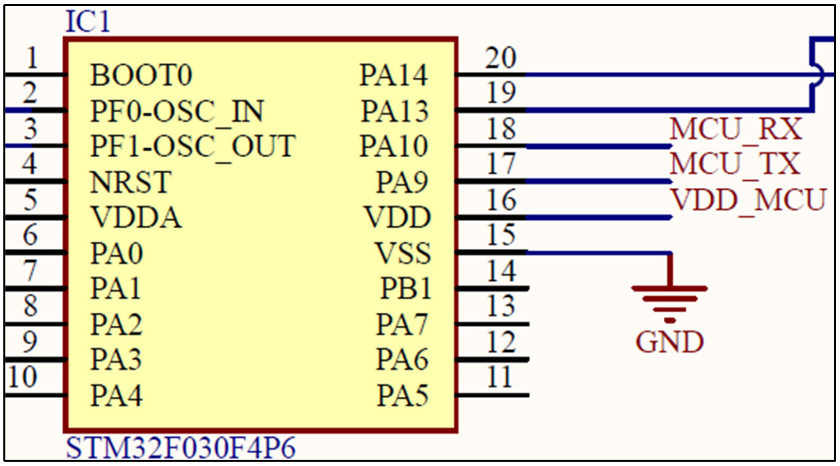

Figure 2.11 Schematic design for USART pins

2.3.7 Schematic Design of Voltage Direct Current (V_{DD})

V_{DD} (Pin16) is typically used to provide the main supply voltage to the MCU. The MCU datasheet recommends using a power supply schematic, depicted in Figure 2.12, to ensure an appropriate V_{DD} voltage for the MCU. It is advisable to position capacitors as close as possible to the V_{DD} to mitigate the effects of ripples, parasites, and external resonance.

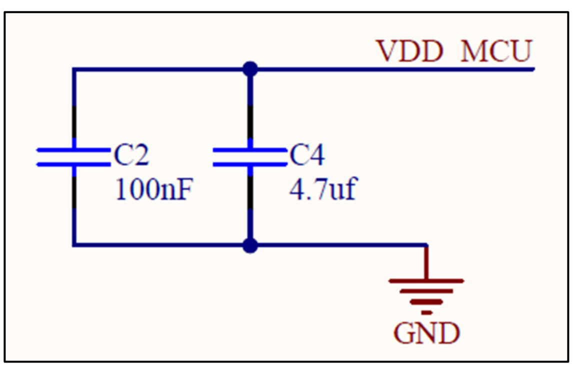

Figure 2.12 Schematic design for V_{DD}

2.3.8 Schematic Design of Voltage Source Ground (V_{SS})

The V_{SS} (Pin15) serves as the ground or reference voltage for the MCU. We need to ground the last pin of the MCU, V_{SS}.

2.4 Schematic Design of the BLE HC-05 Module

In the Prototype WWD, we use the HC-05 module to transmit data from the MCU to a smart device. Following the schematic configuration shown in Figure 2.13, it is necessary to connect the module's pins to the corresponding pins on the MCU.

As mentioned before, we should connect Pin1 and Pin2, designated as USART, to the MCU's USART. Pin12 is responsible for supplying a 3.3V power source to the module, so we should connect it to the MCU's V_{DD}.

The design of the Prototype WWD utilizes three other pins (Pin13, Pin21, and Pin22) included in the HC-05 module. We should ground these pins, as recommended in the manufacturer's datasheet. Moreover, we should ground Pin34 using a 10KΩ resistor.

In this design of the Prototype WWD, the power supply block facilitates the simultaneous activation of both the MCU and HC-05 modules.

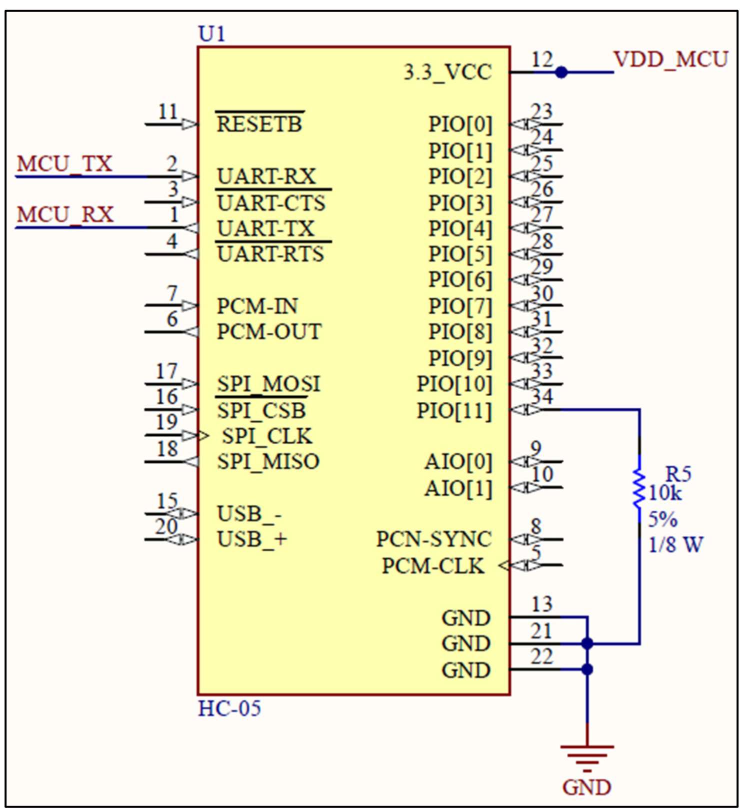

Figure 2.13 Schematic design for the HC-05 module

2.5 Schematic Design of Sensors Block

The next step in designing this Prototype WWD involves the sensors block, depicted in schematic Figure 2.14, which is created with consideration for voltage division.

Resistive, capacitive, and potential sensors are three distinct types of sensors used in various applications, each utilizing different principles to measure and respond to changes in the surrounding environment.

Resistive sensors operate on the principle of changing electrical resistance in response to an external stimulus. This stimulus could be pressure, temperature, light, or any other factor that affects the resistance of the material. As the external condition changes, the resistance of the sensor material changes proportionally. This change in resistance is then measured to determine the magnitude of the stimulus. Resistive sensors are commonly found in pressure sensors, temperature sensors, and force sensors.

Capacitive sensors function based on the principle of changes in capacitance, which is the ability of a system to store an electric charge. The capacitance of the sensor varies with changes in the nearby environment. When the sensor is influenced by external factors like proximity or touch, the capacitance changes. These changes are detected and used to determine the presence or absence of an object or the proximity of another object. Capacitive sensors are used in touchscreens, proximity sensors, and humidity sensors.

Potential sensors, also known as voltage sensors, measure the electrical potential (voltage) in a system. They are designed to detect changes in voltage and convert them into a usable signal. When the voltage in the system changes due to an external stimulus, potential sensors detect these changes and provide an output signal proportional to the alteration in voltage. Potential sensors are commonly used in applications such as voltage monitoring, battery level measurement, and electrical circuit analysis.

We choose resistive sensors for specific reasons. The superiority of resistive sensors over other types, such as capacitive or potential sensors, depends on the specific requirements of the application. Each type of sensor has its advantages and disadvantages, and the choice between them depends on factors like sensitivity, cost, power consumption, and environmental conditions. Here are some situations where resistive sensors might be considered preferable:

- Simplicity and Cost
  Resistive sensors are often simpler and less expensive to manufacture compared to capacitive or potential sensors. When cost is a critical factor, using resistive sensors is the preferable choice.

- Linearity
  In certain applications, resistive sensors offer a linear relationship between the measured parameter and the electrical output. This linearity simplifies calibration and data interpretation.

- Robustness
  Resistive sensors can be more robust in harsh environmental conditions. They may withstand factors like temperature variations, mechanical stress, and contaminants better than some capacitive sensors, making them suitable for rugged applications.

- Compatibility
  Resistive sensors can be compatible with a wide range of materials, making them versatile in various sensing applications. They can be applied to measure parameters such as pressure, temperature, and force with the appropriate resistive material.

- Power Consumption
  Depending on the specific design and application, resistive sensors may consume less power compared to some capacitive sensors. This can be advantageous in battery-operated or low-power devices.

Capacitive and potential sensors have their own strengths and are preferred in scenarios where their characteristics align with the needs of the system. Ultimately, we choose resistive sensor technology by considering factors such as accuracy, sensitivity, power requirements, and the operating environment.

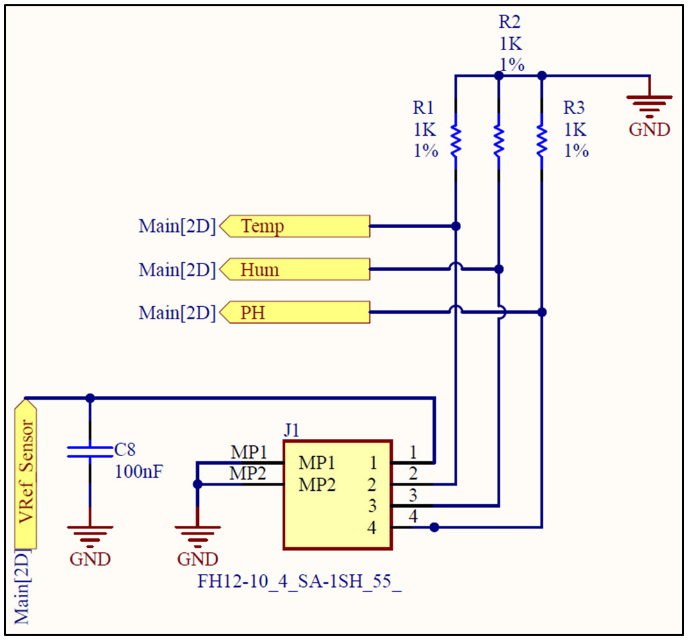

Figure 2.14 Schematic design for the sensors block

As shown in Figure 2.14, we utilize a four-pin connector, "J1". We ground MP1 and MP2, the two shield-side pins of the connector, to safeguard against external parasitic resonance and ripples, ensuring the connector's protection. For this Prototype WWD, we consider sensors comprising three different types of resistive sensors and one common ground. These sensors include Temperature, Humidity, and pH (Reserved) sensors. In terms of progress and development, Temperature and Humidity sensors are not standardized. As a result, the resistivity values may vary among different sensors. To address this in Figure 2.14, we select resistors R1, R2, and R3 in the schematic as 1KΩ with 1% tolerance accuracy as sample values.

However, during the assembly of components, we choose the appropriate resistors with values matching those of the sensors. We individually connect each of these resistors to its respective sensor and then link them to Pin2, Pin3, and Pin4 of the J1 connector.

The operation of the sensors block, as shown in Figure 2.14, relies on V_{Ref_Sensor}, which is V_{DDA} and equal to 3.3V. This voltage is consistent for all sensors since they share a common interface. As the temperature or humidity changes, the resistance of each sensor will change, leading to a variation in the voltage values across the sensor pins.

Consequently, the MCU measures the new analog voltage and converts it into a digital value using its ADC inputs. This digital value is subsequently transmitted to a smart device.

In addition, we employ capacitor C8 to safeguard V_{Ref_Sensor} from external parasitic resonance and ripples, we should position it as close as possible to Pin1 of the J1 connector.

2.6 Schematic Design of Power Management Block

The power management block is the last block in the design of this Prototype WWD. We have designed it in accordance with the manufacturer's MCU datasheet and other specified requirements and components. Figure 2.15 illustrates the schematic representation of the power management block, with each component detailed in the following sections.

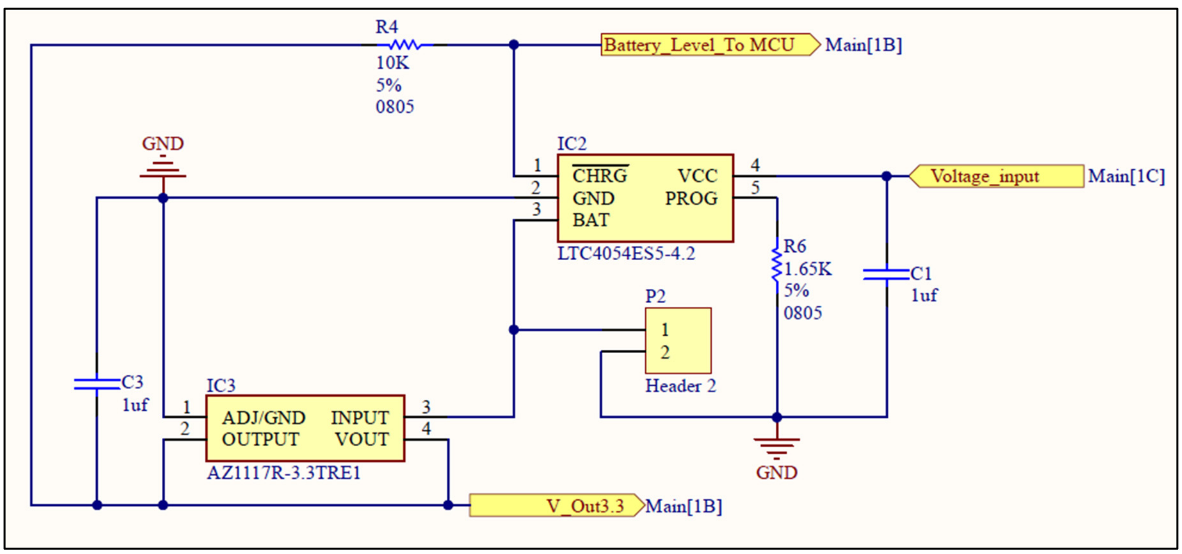

Figure 2.15 Schematic design for power management block

2.6.1 Schematic Design of the Regulator IC in the Power Management Block

Referring to the schematic depicted in Figure 2.15, we can begin with P2 (Header 2), which comprises two pins designed for connecting the battery. The Prototype WWD can utilize various types of batteries, but it is adequate to use a Lithium-ion (Li-ion) Polymer battery with a nominal voltage output of 3.7V and a capacity of 500mAh.

We connect P2 to the regulator AZ1117R-3.3TRE1, ensuring that the input voltage is regulated to 3.3V. The MCU, sensors, and HC-05 BLE module need to use this regulated voltage to work effectively.

The AZ1117 series of regulators offer current limiting and thermal shutdown features. The circuit incorporates a trimmed bandgap reference to ensure output voltage accuracy within 1% for versions such as 1.5V, 1.8V, 2.5V, 2.85V, 3.3V, 5.0V, and adjustable, or within 2% for the 1.2V version.

The current limit is adjusted to guarantee the specified output current and controlled short-circuit current. The on-chip thermal shutdown safeguards against combinations of overload and ambient temperature that could lead to excessive junction temperature (DIODES, 2019).

The AZ1117 series is available in standard power packages, including SOT223, SOT89, TO220-3, TO252-2, and TO263. For the Prototype WWD, we choose the SOT89 package due to its low power consumption, cost-effectiveness, and compact size, as shown in Figure 2.16. (DIODES, 2019).

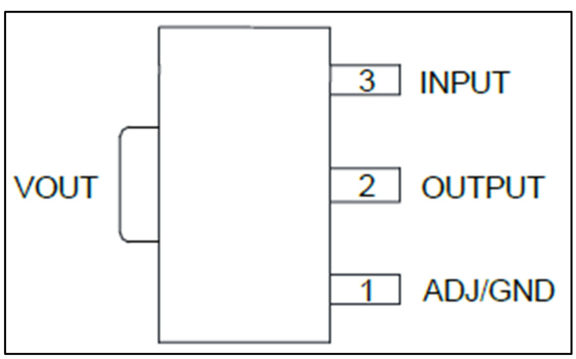

Figure 2.16 SOT89 package of regulator IC
Taken from DIODES (2019, p. 1)

2.6.2 Schematic Design of the Charge IC in the Power Management Block

The power management block includes the LTC4054ES5-4.2 charge IC as another crucial component. This IC is specifically designed for battery charging and operates within an input voltage range of 4.2V to 6.5V.

As mentioned earlier, we can power the MCU during debugging using either an external charger or the debug adapter, eliminating the requirement for the battery. The input voltage is routed through the charge IC and then regulated to a stable 3.3V by the regulator, ensuring a reliable power supply for the Prototype WWD.

In Figure 2.17, we can see the typical application and recommended schematic design provided by the manufacturer, along with a sample charge cycle diagram for a 750mAh battery. (LINEAR TECHNOLOGY, 2010).

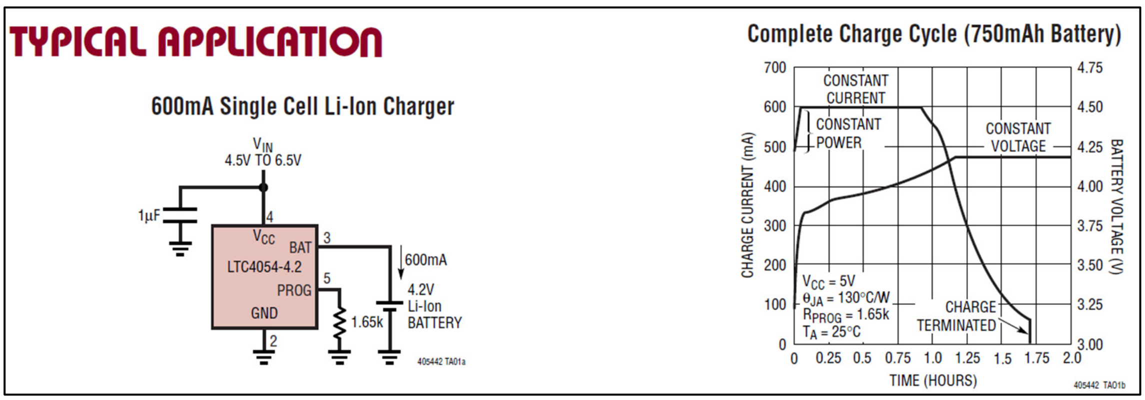

Figure 2.17 Typical application schematic of charge IC and diagram of complete charge cycle for a 750mAh battery
Taken from LINEAR TECHNOLOGY (2010, p. 1)

The LTC®4054 is a comprehensive linear charger designed for single-cell Li-ion batteries, providing constant-current and constant-voltage charging. With its thin SOT package and minimal external component requirements, the LTC4054 is highly suitable for portable applications (LINEAR TECHNOLOGY, 2010).

It is specifically engineered to adhere to Universal Serial Bus (USB) power specifications. Unlike other chargers, the LTC4054 eliminates the need for an external sense resistor and a blocking diode due to its internal Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) architecture (LINEAR TECHNOLOGY, 2010).

The charge current is regulated using thermal feedback to control die temperature to ensure safe operation under high power conditions or elevated ambient temperatures. The charge voltage remains fixed at 4.2V, while the charge current can be programmed externally using a single resistor. The LTC4054 automatically concludes the charging cycle when the charge current drops to 1/10th of the programmed value after reaching the final float voltage (LINEAR TECHNOLOGY, 2010).

When the input supply, whether from a wall adapter or USB source, is disconnected, the LTC4054 enters a low current state, significantly reducing battery drain to less than 2mA. Additionally, the LTC4054 can be put into shutdown mode, minimizing the supply current to 25mA (LINEAR TECHNOLOGY, 2010).

Figure 2.18 displays the top view of the TSOT-23 package and pin configuration of the LTC4054ES5-4.2 charge IC, which we use in the design of the power management block.

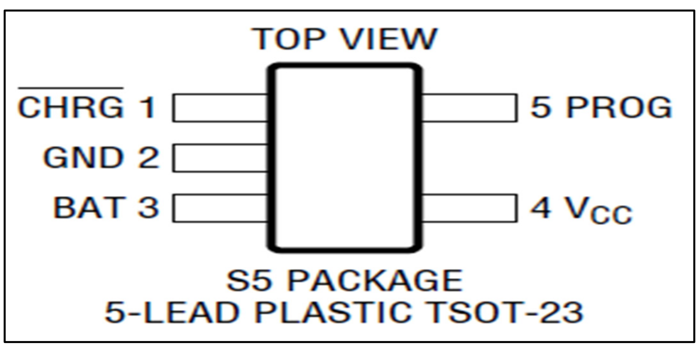

Figure 2.18 TSOT-23 package of LTC4054ES5-4.2
Adapted from LINEAR TECHNOLOGY (2010, p. 2)

According to the charge IC datasheet, we use a 1.65KΩ resistor, R6, for the battery fast charging mode. We use another resistor, R4, with a value of 10KΩ, for voltage division between the CHRG and regulator output. This voltage division facilitates the indication of battery level by the MCU.

We position capacitors C1 and C3 in close proximity to the circuit's input and output, respectively, to safeguard the power management circuit from unwanted ripple and resonance, as shown in Figure 2.15.

We designed the power management block to function with or without a battery. When a battery is connected, the Prototype WWD utilizes its power. However, when the Prototype

WWD is connected to a charger or an adaptor debugger, it draws power from its power supply and simultaneously charges the battery.

2.7 Designing the Rigid PCB for the Prototype WWD

We use the Altium Designer software (Version 21.6.4) to create the final PCB layout, taking into account the critical specifications of each section and element. Figure 2.19 depicts the arrangement of these elements in 2D, while Figure 2.20 illustrates their arrangement in 3D.

We integrate a Faraday cage onto the PCB to shield the wearable device's circuitry from unwanted disturbances such as noise, ripples, and resonance. Therefore, we use a polygon among the traces and connections.

For the final version of the Prototype WWD, we design the PCB with dimensions of 20x30mm, utilizing two layers, and construct it from rigid fiberglass material with a thickness of 1.6mm.

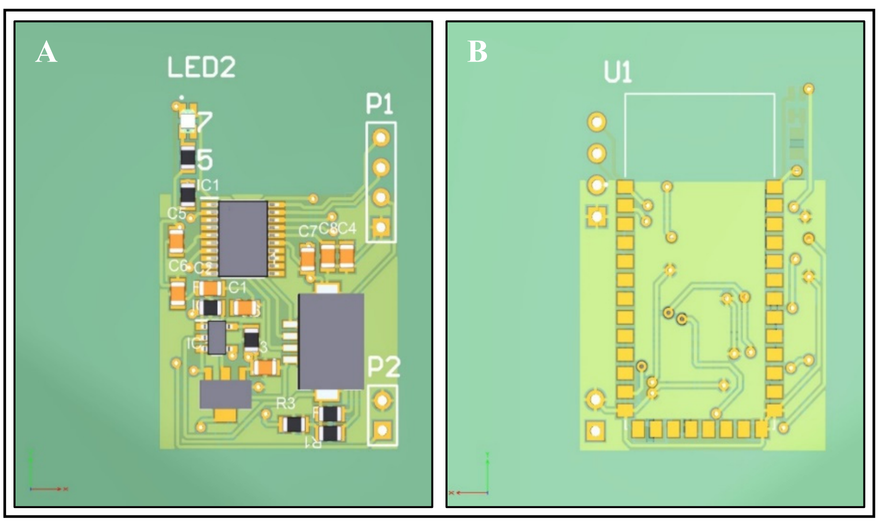

Figure 2.19 PCB layout of the Prototype WWD: (A) front, (B) back

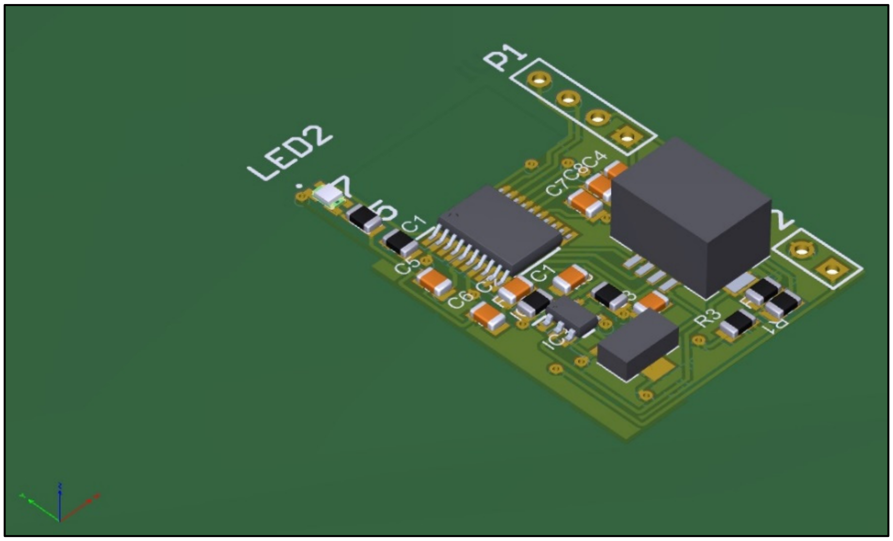

Figure 2.20 3D PCB layout of the Prototype WWD

The initial fabricated PCBs, as depicted in Figure 2.21, exhibited poor quality. During assembly and soldering, some connections and traces detached, and certain holes were filled with excess copper. Therefore, we decided to remanufacture them in green PCB with improved detail and quality, as shown in Figure 2.22.

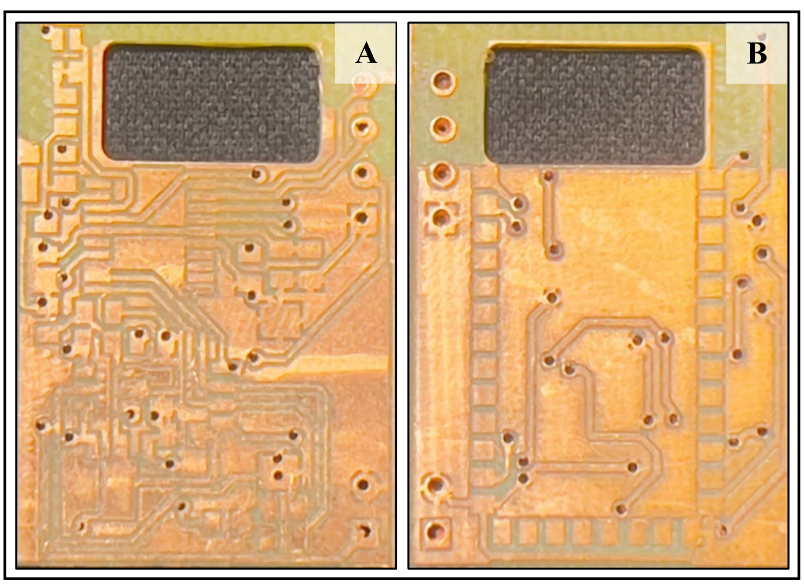

Figure 2.21 Initial PCB fabrication: (A) front, (B) back

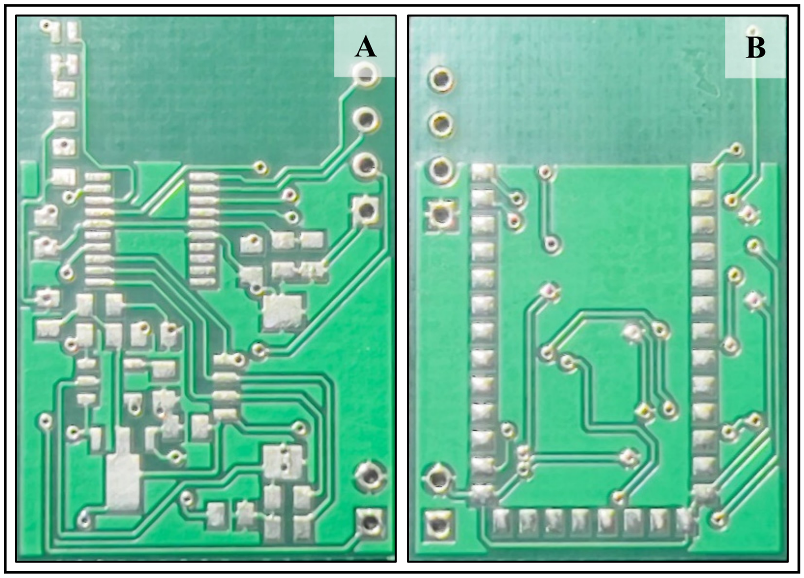

Figure 2.22 Remanufactured PCB: (A) front, (B) back

2.8 Designing the Ultimate Flexible WWD Using the nRF51822 MCU

We consider flexibility as a crucial key objective in designing a WWD. The initial prototype, which incorporated a rigid fiberglass board, lacked the desired level of flexibility. Therefore, it cannot be considered a truly flexible WWD. Nevertheless, the device exhibit acceptable functionality and a logical design. Its dimensions are adaptable, power consumption is minimal, cost is reasonable, and operation is efficient.

We replaced the STM32 series MCU with the nRF51 series MCU, specifically the nRF51822 to address the flexibility issue. This alternative MCU is smaller in size and incorporates embedded BLE technology, eliminating the need for the rigid HC-05 BLE module to transmit data. As a result, we can now fabricate the device on a polyimide material, enabling it to achieve the desired flexibility. Therefore, we need to redesign certain components in accordance with the recommendations for the nRF51822 MCU.

2.8.1 Attributes of the nRF51822 MCU

The nRF51822 is a highly capable single-chip solution designed for Ultra-Low Power (ULP) wireless applications. The nRF51822 is compatible with both BLE and 2.4GHz protocol stacks, making it a versatile option (Figure 2.23) (Nordic Semiconductor, 2014b).

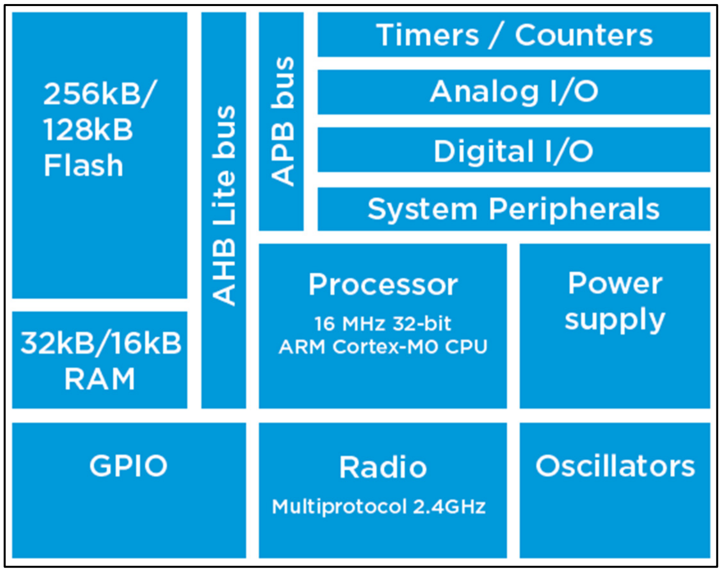

Figure 2.23 The nRF51822 attributes
Taken from Nordic Semiconductor (2014b, p. 1)

The device incorporates the Programmable Peripheral Interconnect (PPI) system to facilitate efficient peripheral communication without CPU intervention, which features a 16-channel bus. This enables direct and autonomous interaction between system peripherals, resulting in predictable latency times and power-saving benefits by allowing the CPU to remain idle (Nordic Semiconductor, 2014b).

The nRF51822 operates in two global power modes, On and Off. However, all system blocks and peripherals have individual power management control. This allows for automatic switching between the Run and Idle modes for specific system blocks based on their requirements for accomplishing particular tasks (Nordic Semiconductor, 2014b).

The performance of the nRF51822 is underpinned by its new radio, which supports BLE and maintains compatibility with Nordic Semiconductor's nRF24L Series products.

The radio's output power can be scaled from a maximum of +4dBm to -20dBm in increments of 4dB. At each level, sensitivity is improved, offering a range of sensitivity values (dependent on the data rate) from -96 to -85dBm, with a sensitivity of -93dBm for BLE.

Here are some other notable features of the MCU (Nordic Semiconductor, 2014b):

- Multiprotocol 2.4GHz radio
- Pin compatible with other nRF51 Series devices
- Received Signal Strength Indicator (RSSI)
- Full set of digital interfaces including: SPI/ 2-wire/ Universal Asynchronous Receivers/Transmitters (UART)
- 10-bit ADC
- 128-bit Advanced Encryption Standard (AES)
- Low-cost external crystal 16MHz ± 40ppm
- Low-power 16MHz crystal and RC oscillators
- ULP 32KHz crystal and RC oscillators
- Wide supply voltage range (1.8V to 3.6V)
- On-chip Direct Current DC/DC buck converter
- Individual power management for all peripherals
- Package options: 48-pin 6x6 QFN/WLCSP, Thin-CSP

2.8.2 Application of the nRF51822 MCU

Some important applications of this MCU are as (Nordic Semiconductor, 2014b):

- BLE applications
- Wearables
- Proximity and security alert tags
- Healthcare and lifestyle sensors

2.8.3 Power Supply of the nRF51822 MCU

The nRF51 offers three different options for power supply (Nordic Semiconductor, 2014):

Internal Low Drop-Out (LDO) setup:

In this mode, the DC/DC converter is disabled, and the system power is directly generated from the supply voltage, V_{DD}. This setup can be used either as the sole option or in combination with the DC/DC converter configuration.

DC/DC converter setup:

The nRF51 features a DC/DC buck converter that efficiently converts the battery voltage to a lower internal voltage, minimizing power loss. The converted voltage is then used as input for the linear regulator.

When the supply voltage drops to the lower limit of the voltage range, the DC/DC converter can be disabled, and the LDO regulator can be employed for low supply voltages. During radio events, when only the low current regulator is required internally, the operation of the DC/DC converter is automatically suspended. This capability is particularly beneficial for applications that utilize battery technologies with nominal cell voltages higher than the minimum supply voltage with DC/DC enabled.

By reducing the supply voltage level from a higher voltage to a lower voltage, the peak power drain from the battery is decreased. When used with a 3V coin-cell battery, the peak current drawn from the battery is reduced by approximately 25%.

Low voltage mode setup

In this mode, the devices can operate with a steady 1.8V supply provided externally.

The pin assignment of the nRF51822 MCU with package code QFN48 is shown in Figure 2.24 (Nordic Semiconductor, 2014):

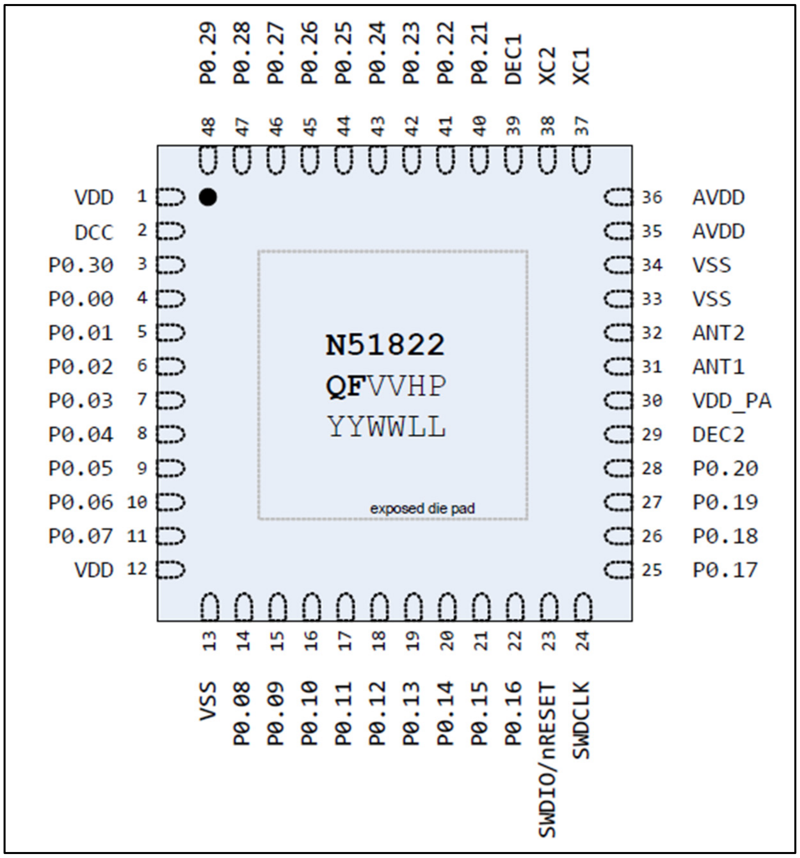

Figure 2.24 Pin assignment of the nRF51822
with package code QFN48
Taken from Nordic Semiconductor (2014, p. 11)

2.9 Schematic Design for the Ultimate Flexible WWD with the nRF51822 MCU

Upon comparing the schematic designs of the Prototype WWD (Figure 2.2) with the ultimate flexible WWD (Figure 2.25), it is evident that the power management block, sensors block, and LED block remain unchanged. However, we have added a USB Type-C connector to the power management block as the J1 connector. This USB Type-C connector serves the purpose of charging the device's battery using an external adaptor. Figure 2.25 illustrates the schematic design of the ultimate flexible WWD.

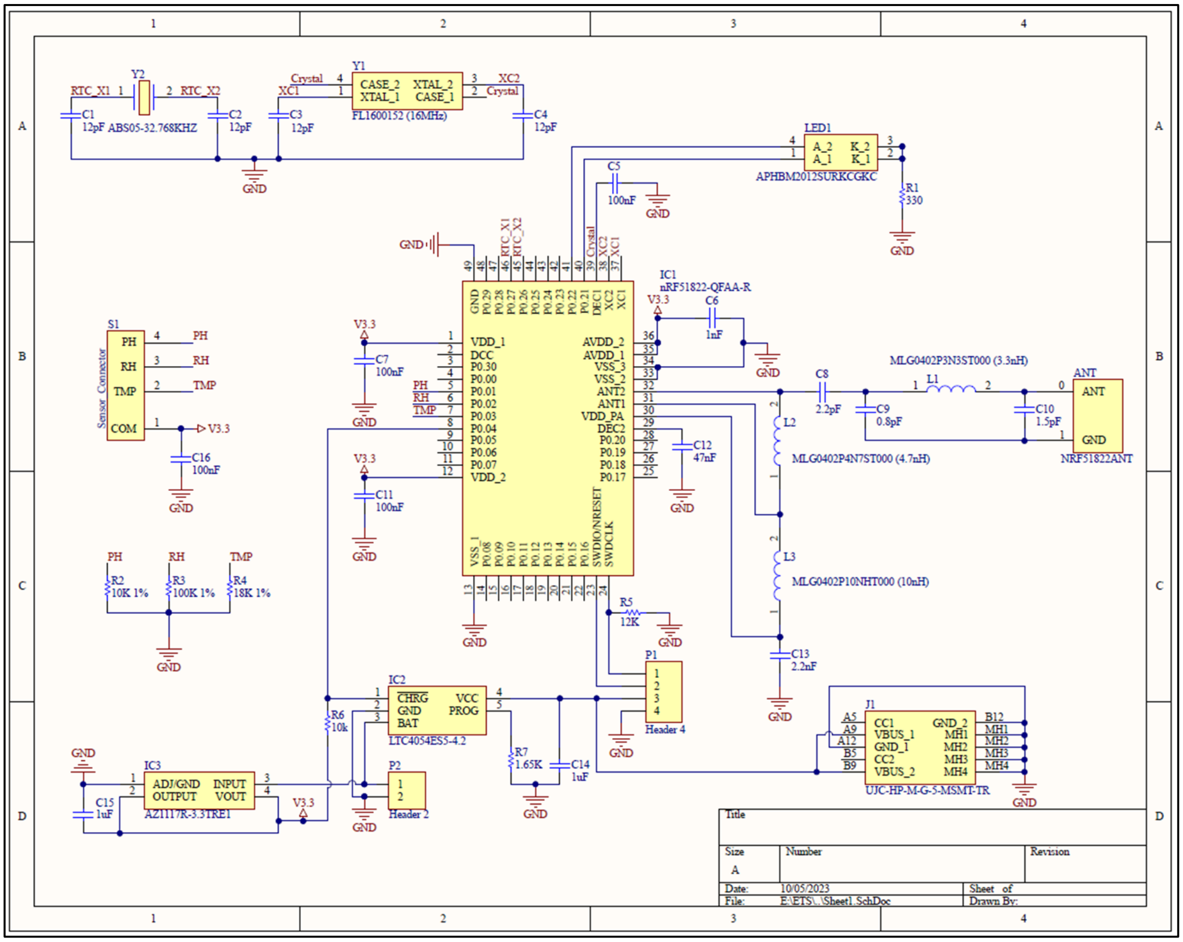

Figure 2.25 Schematic design of the ultimate flexible WWD with the nRF51822 MCU

2.9.1 Schematic Design for V_{CC} Pins of nRF51822 MCU

The nRF51822 MCU employed in the design of the flexible WWD consists of a total of 48 pins. Let's delve into the functionality of each pin.

Pin1 and pin12 are specifically designated as V_{DD_1} and V_{DD_2}, respectively, in the MCU. These pins serve as the V_{CC} (3.3V supply voltage) for the flexible WWD. Furthermore, we utilize pin12 (V_{DD_2}) as the input voltage for the common base of the sensors block.

The nRF51822 MCU's datasheet recommends the use of capacitors C7 and C11 near pin1 and pin12, respectively as illustrated in Figure 2.26 to ensure the protection of these crucial pin1 and pin12 against undesirable ripples and resonance.

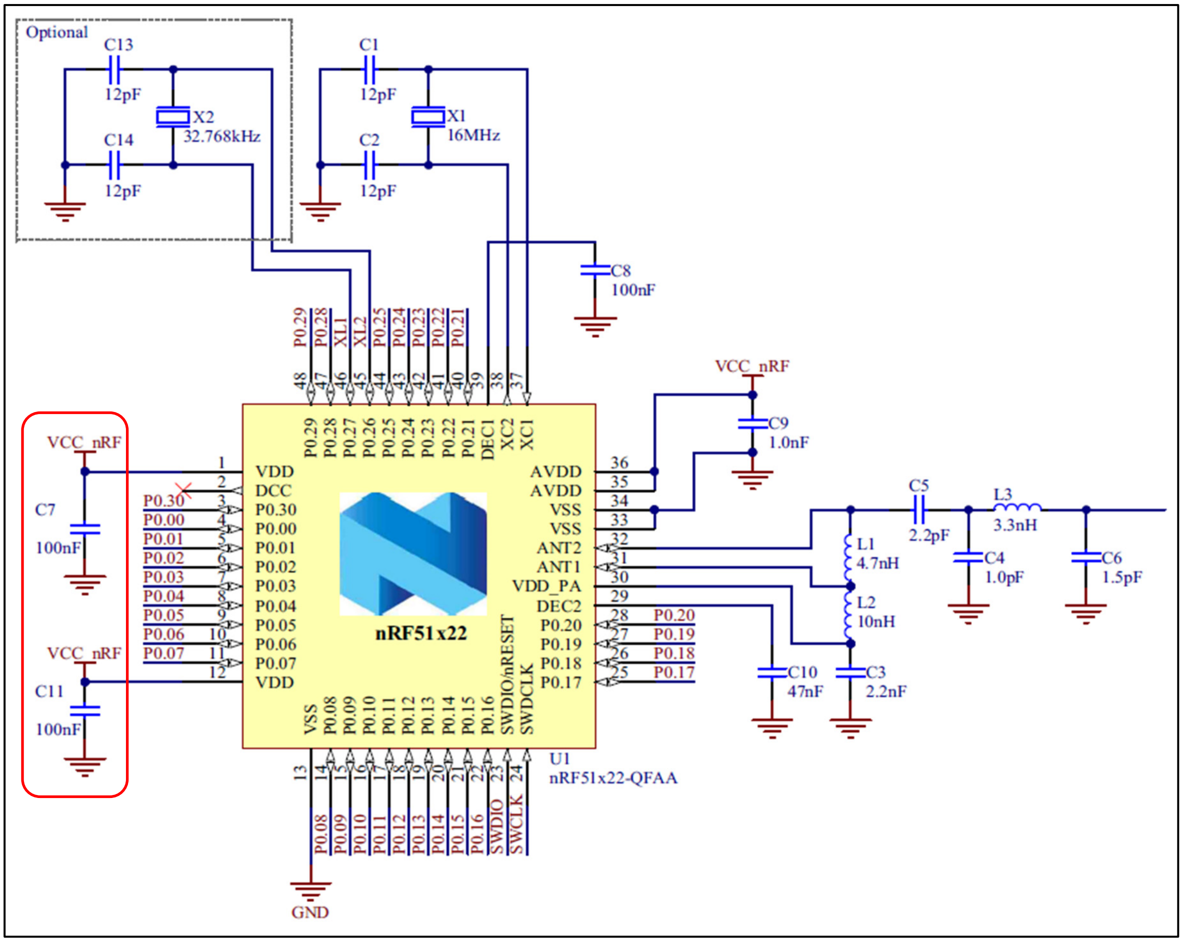

Figure 2.26 Recommended schematic design on nRF51x22
Taken from Nordic Semiconductor (2014, p. 79)

We ground Pin33 (V_{SS_2}) and Pin34 (V_{SS_3}), and connect Pin35 (AV_{DD_1}) and Pin36 (AV_{DD_2}) to V_{CC} in accordance with the recommendations provided in the MCU's datasheet, as depicted in Figure 2.26. It is advisable to follow the suggested design guidelines for these pins to ensure proper functionality and performance.

On the other hand, pin13 (V_{SS_1}) as recommended in the MCU's datasheet in Figure 2.26, it should be grounded to ensure proper functionality. Additionally, it is recommended that pin29 (DEC2) be grounded using a capacitor.

2.9.2 Schematic Design for the ADC Pins of the nRF51822 MCU

Pin5 (P0.01), pin6 (P0.02), and pin7 (P0.03) serve as ADC inputs for sensors in the flexible WWD as shown in Figure 2.25. We reserve Pin5 for the pH sensor, utilize Pin6 for the Humidity sensor, and assign Pin7 to the Temperature sensor. In addition, we can use pin8 (P0.04) as an additional ADC input to indicate the battery charge status.

2.9.3 Schematic Design for the Debug Serial of the nRF51822 MCU

We designate Pin23 and Pin24 as debug serial pins, fulfilling the role of debugging and programming the MCU. These pins are connected through resistor R5 with a value of 12KΩ to pin1 and pin2 of "Header 4", denoted as "P1" in schematic Figure 2.27.

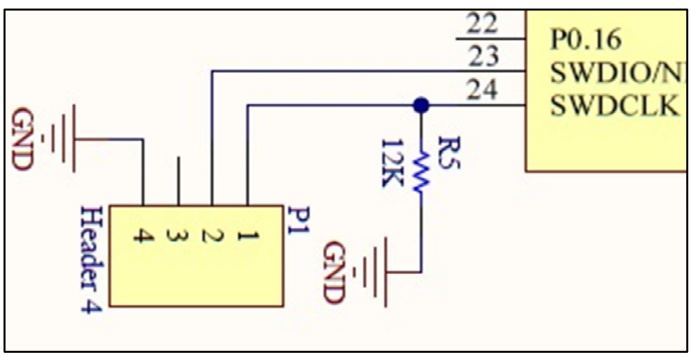

Figure 2.27 Schematic design for the debug serial

2.9.4 Schematic Design for the Antenna of the nRF51822 MCU

To enable data transmission, the MCU's BLE functionality requires the use of an antenna. The MCU's datasheet provides a recommended antenna circuit configuration according to Figure 2.26. Pin30 (V_{DD_PA}), pin31 (ANT1), and pin32 (ANT2) are employed for the antenna circuit. The schematic design for Antenna is illustrated in Figure 2.28.

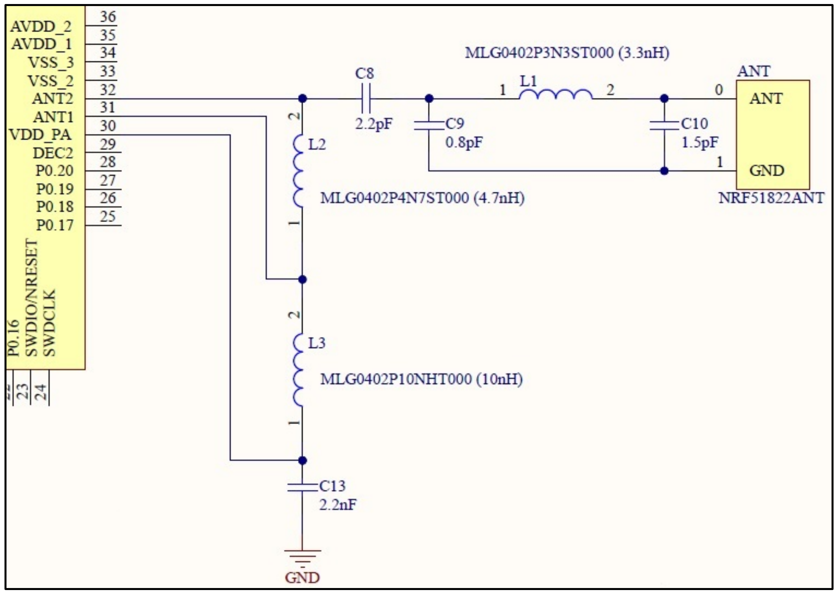

Figure 2.28 Schematic design for the antenna

We align the selected shape of the antenna with that of the HC-05 module's antenna. The utilization of a spiral-shaped antenna aims to enhance its performance and efficiency. The spiral shape is specifically selected for antenna due to its unique characteristics. In this configuration, we bend the antenna into a thin strip and form it into a spiral pattern according to Figure 2.29. This shape offers several advantages, including an increase in the physical length. By extending the antenna length, greater absorption and propagation of waves occur, leading to amplified received and transmitted signal power.

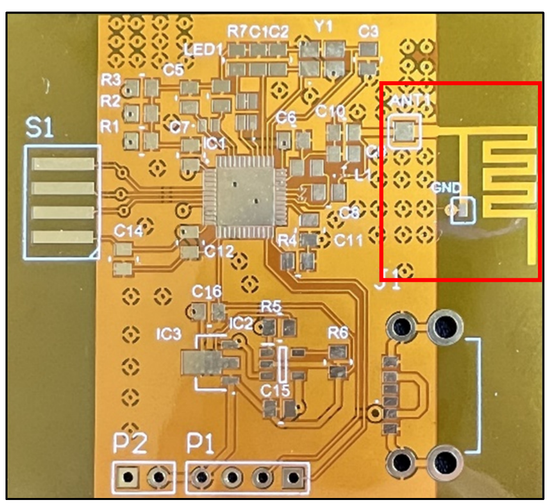

Figure 2.29 Spiral-shaped of antenna

Moreover, the spiral shape enables the antenna to make efficient use of limited space. This feature proves advantageous when integrating the module into various compact devices and tools that have limited space availability. The selection of the spiral antenna design is based on its benefits and its ability to improve wireless communication performance.

2.9.5 Schematic Design for the LED of the nRF51822 MCU

In the flexible WWD, we use Pin40 (P0.21) and Pin41 (P0.22) as digital inputs, similar to the Prototype WWD design depicted in Figure 2.25. We use these pins to connect the LED, which is responsible for indicating different modes of the WWD as well as displaying the charging status.

2.9.6 Schematic Design for the Crystal Oscillator of the nRF51822 MCU

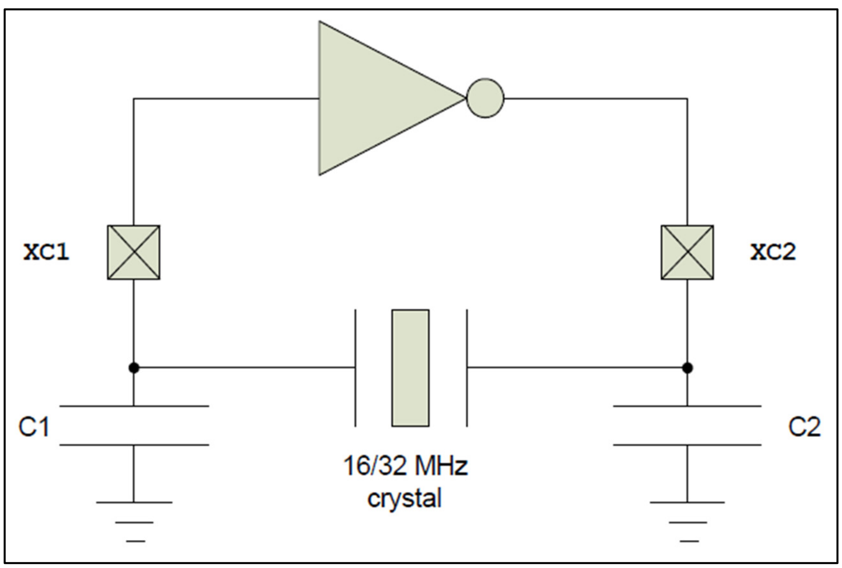

Figure 2.30 The crystal oscillator setup design
Taken from Nordic Semiconductor (2014, p. 28)

We link Pin37 (XC1), Pin38 (XC2), and Pin39 (DEC1) to the primary crystal in the circuit. The crystal oscillator can be governed by an external crystal with a frequency of either 16MHz or 32MHz. However, the system clock always operates at 16MHz. It is crucial to ensure that the load capacitance matches the specifications provided in the crystal's datasheet to achieve the correct oscillation frequency. The diagram in Figure 2.30 illustrates the connection of the crystal to the 16/32MHz crystal oscillator (Nordic Semiconductor, 2014).

C1 and C2 in Figure 2.30 refer to ceramic SMD capacitors that are connected between each terminal of the crystal and the ground. It is important for the load capacitors, C1 and C2, to have the same value. To ensure reliable operation, the crystal's load capacitance, shunt capacitance, equivalent series resistance (RS,X16M), and drive level must adhere to the specifications set for a 16MHz frequency (Nordic Semiconductor, 2014).

It is recommended to opt for a crystal with an RS,X16M value lower than the maximum if the load capacitance and/or shunt capacitance is high. This choice will result in a faster startup time and lower current consumption. By utilizing a lower load capacitance, both the startup time and current consumption can be reduced (Nordic Semiconductor, 2014).

We establish the connection to the RTC crystal in the circuit using Pin45 (P0.26) and Pin46 (P0.27). The 32.768KHz crystal oscillator is specifically designed to operate with a quartz crystal in parallel resonant mode. To ensure an accurate oscillation frequency, it is essential to match the load capacitance with the specifications provided in the crystal datasheet. The configuration for connecting the crystal to the 32.768KHz crystal oscillator is illustrated in Figure 2.31.

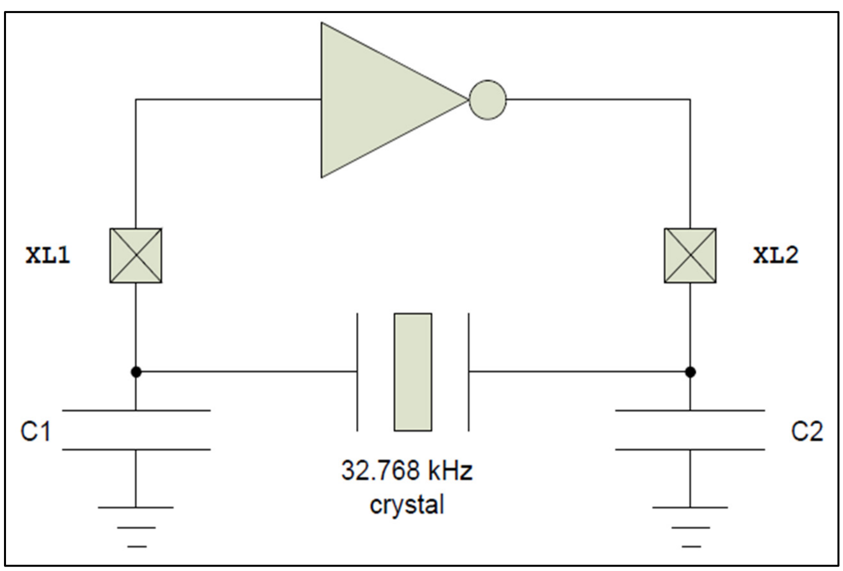

Figure 2.31 RTC crystal oscillator setup design
Taken from Nordic Semiconductor (2014, p. 29)

Same as the main crystal oscillator, it is important for the load capacitors, C1 and C2 in Figure 2.31, to have the same value. Alternatively, the 32.768KHz RC low-frequency oscillator can be used as a substitute for the 32.768KHz crystal oscillator. (Nordic Semiconductor, 2014).

The 32.768KHz RC oscillator does not require any external components. The low-frequency clock can be synthesized from the high-frequency clock, eliminating the need for a crystal and reducing costs. However, it is important to note that using the RC oscillator increases average power consumption as the high-frequency clock source needs to remain active (Nordic Semiconductor, 2014).

The schematic design for crystal oscillators are illustrated in Figure 2.32. We connect Pin37 of the MCU through the Net label XC1, Pin38 through the Net label RTC_XC2, Pin46 through the Net label RTC_X1, and Pin45 through the Net label RTC_X2.

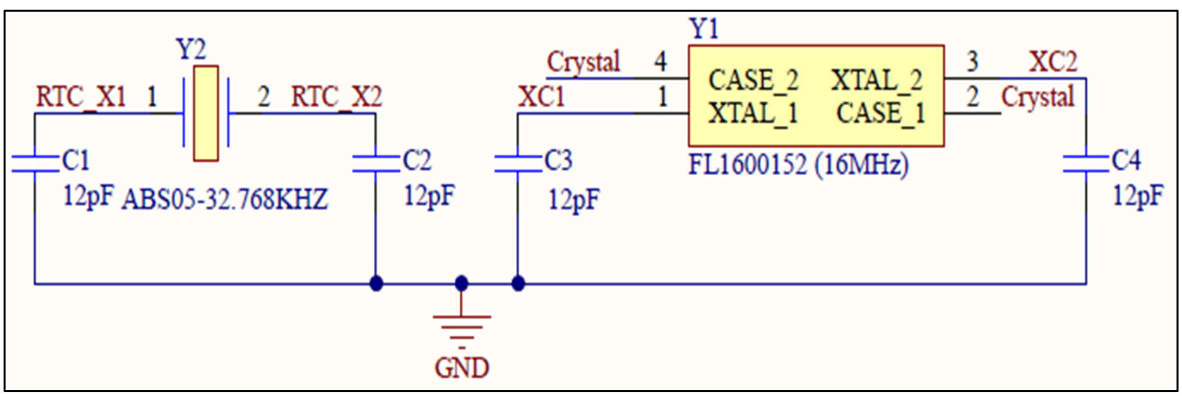

Figure 2.32 Schematic design for the crystal oscillators

2.10 Schematic Design for the Sensors Block of the nRF51822 MCU

The sensor types are the same as the sensors we use in prototype WWD, but we need to design the sensors in a manner that facilitates easy connection to the 'S1' input. In the redesign of the sensors for the flexible WWD, we use carbon tape because of its high conductivity and user-friendly nature.

As shown in schematic Figure 2.33, we use resistors R2, R3, and R4, each having resistances of 10KΩ, 100KΩ, and 18KΩ with a 1% tolerance, for the pH (as a reserved sensor), Humidity (RH), and Temperature (TMP) sensors, respectively.

It is crucial for the sensor's resistance to be in alignment with the resistor's resistance. If there are any changes in the sensor's resistance, it becomes necessary to replace the resistors with suitable alternatives.

The sensors we have utilized are printed on a polyamide sheet. However, they possess the flexibility to be printed on a specialized bandage designed for surgical wound coverage. With this innovative approach, one end of the bandage can be securely placed over the wound, while the other end can be firmly attached to the flexible WWD using carbon tape or an alternative conductive tape. This method enables direct attachment of the flexible WWD and its accompanying flexible battery to the bandage, eliminating the necessity for wires or connectors. This minimizes potential disruptions or discomfort for the patient, enhancing overall convenience.

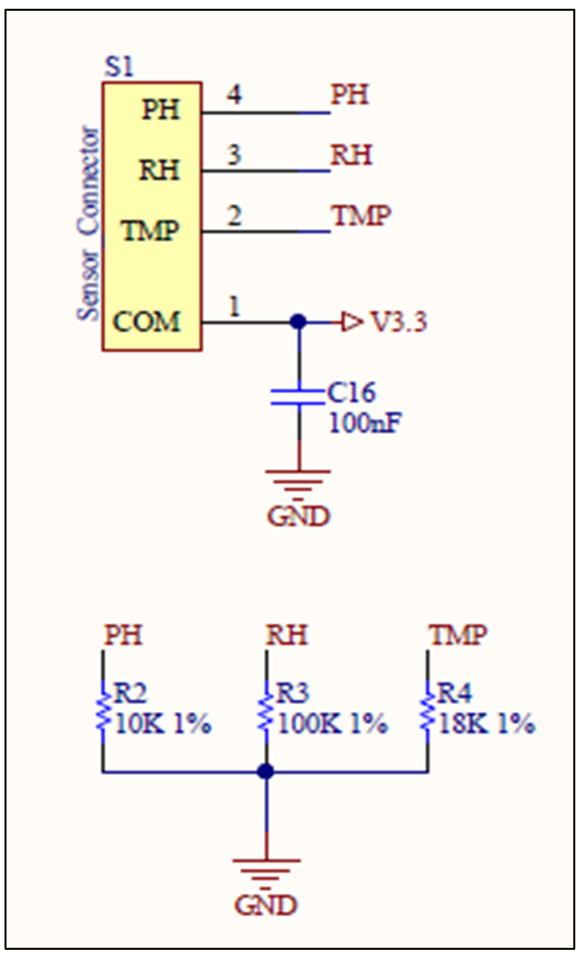

Figure 2.33 Schematic of the sensors block

2.11 Schematic Design for the Charging Block of the nRF51822 MCU

We design the charge block in the nRF51822 closely to mirror that of the Prototype WWD, ensuring continuity and familiarity in our design. Furthermore, to enhance the charging capabilities of the wearable device, we have introduced a Type-C USB port as a notable addition to the charging block. This Type-C USB port serves as the gateway for conveniently and efficiently recharging the flexible WWD's battery.

The schematic detail of the Type-C USB port is depicted in schematic Figure 2.34. This enhancement not only improves the user experience by offering a versatile charging solution but also aligns seamlessly with the evolving standards of connectivity and convenience in the realm of wearable technology.

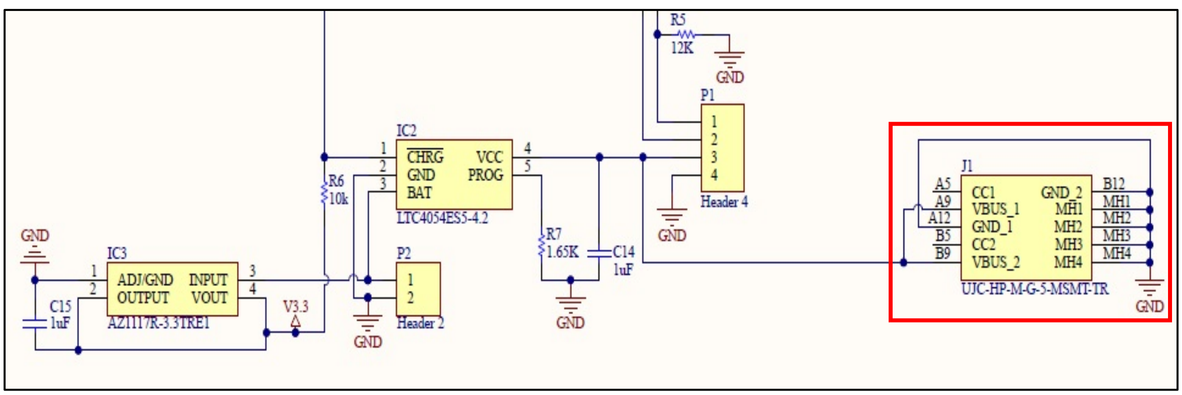

Figure 2.34 Schematic of the charging block with Type-C USB port

2.12 Designing the Ultimate Flexible PCB for the WWD

The final layout design of our flexible WWD, as illustrated in Figure 2.35, is the culmination of meticulous planning and design using Altium Designer software (Version 21.6.4).

We made every component selection and decision in our design process with careful consideration of our specific requirements. We ensured that our design adhered to the recommendations provided by manufacturers and met all the essential prerequisites. This comprehensive approach allowed us to create our ultimate flexible WWD.

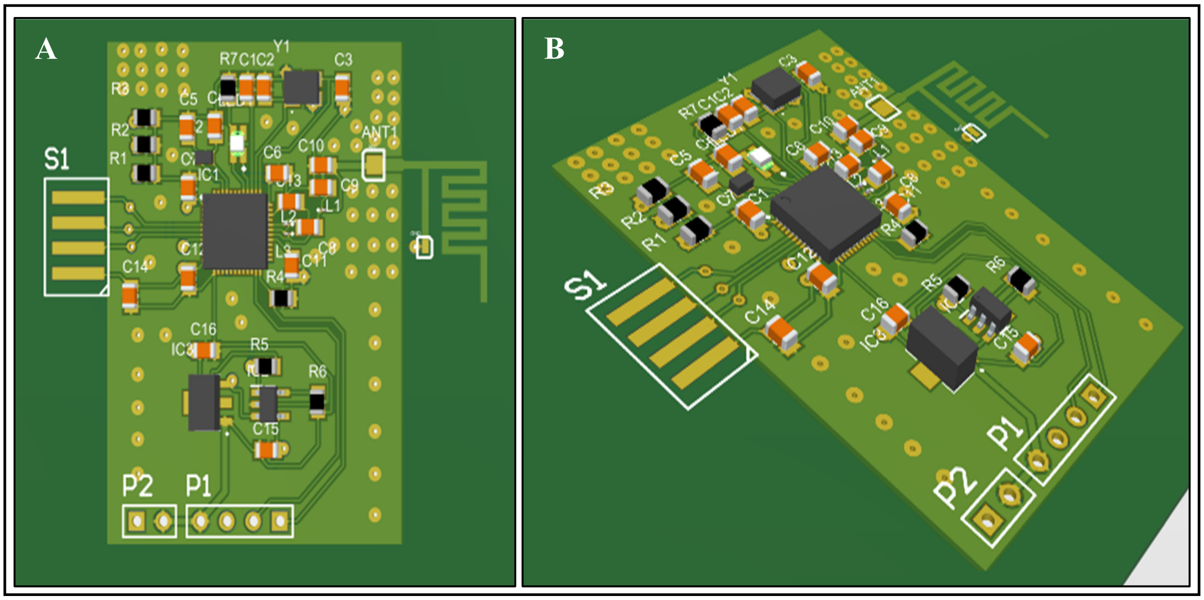

Figure 2.35 Layout design of flexible WWD: (A) 2D layout, (B) 3D layout

We meticulously designed the flexible PCB for our WWD to meet our specific requirements. This PCB, as showcased in Figure 2.36, comprises two layers and measures 50x41mm. It is created using polyimide flex material, which is available in various colors, including transparent, black, and the traditional copper-colored. The thickness of this polyimide material is precisely 0.1mm.

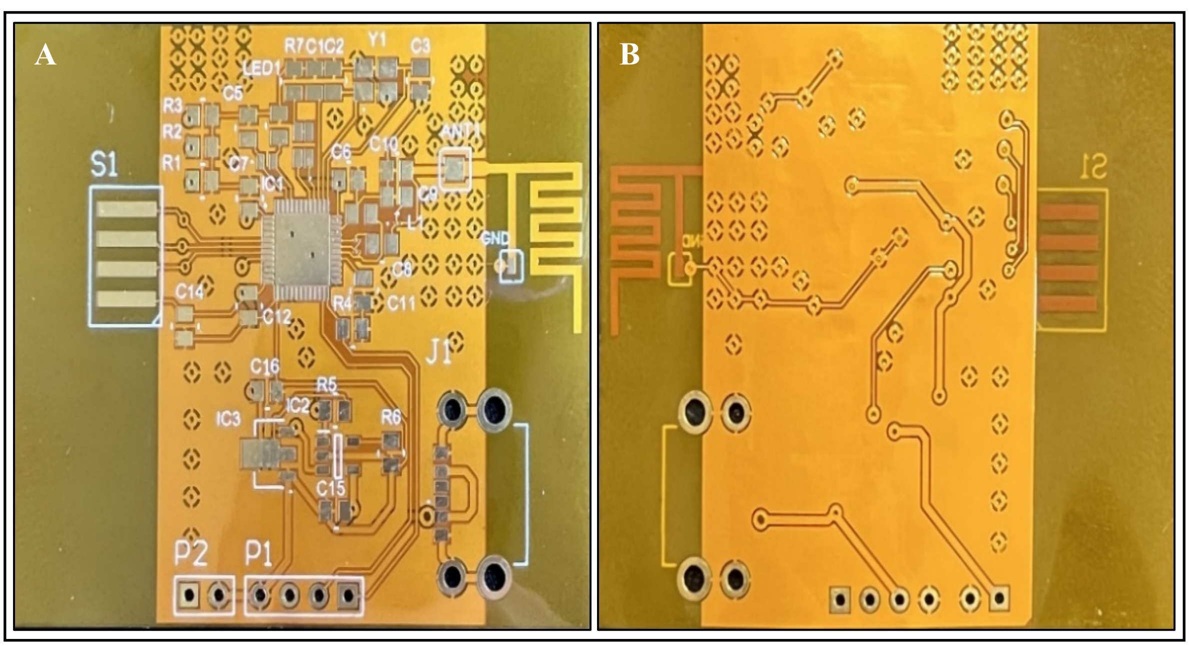

Figure 2.36 Fabricated flexible PCB, (A) front, (B) back

2.13 Battery for the WWD

The ideal battery should provide a voltage range of approximately 4.2V to 5V and have a capacity of around 500mAh for our flexible WWD. Li-ion batteries are readily available in the market and are known for their reliability. However, they lack the flexibility of the polyimide material we have used in our device.

In our design, we have securely housed a compact Li-ion battery, ensuring a stable voltage supply to keep our flexible WWD operating smoothly.

It is important to note that while flexible batteries offer versatility, they tend to be less efficient and have shorter operational lifespans compared to Li-ion batteries. Nonetheless, there are situations and specific applications where flexible batteries can prove useful within the flexible WWD design, so they are not entirely excluded. A flexible battery is shown in Figure 2.37.

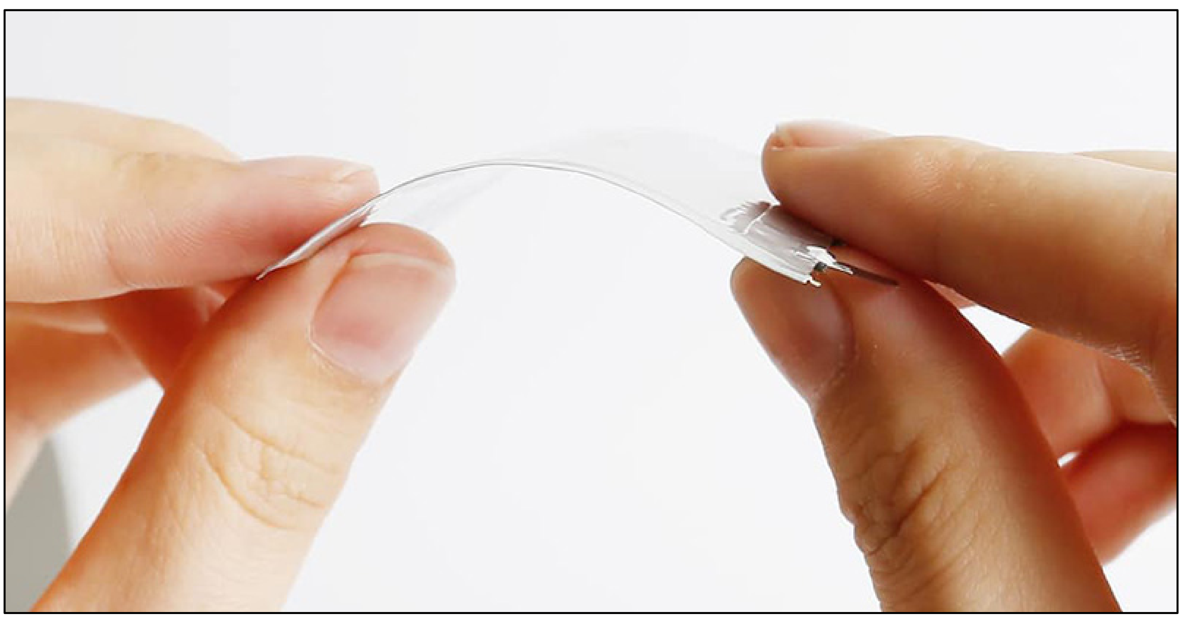

Figure 2.37 Flexible battery
Taken from https://himaxelectronics.com/the-key-to-fully-flexible-electronics-flexible-lithium-batteries/, (2020)

2.14 Conclusion

In conclusion we designed and developed the wireless wearable device utilizing the nRF51822 MCU, with a focus on ultra-low power consumption for wireless applications. The device incorporates various features, including BLE compatibility, 2.4GHz protocol support, and versatile power management options. It aims to provide a platform for applications such as BLE connectivity, wearables, and healthcare sensors.

Key components and functionalities of the WWD include a multiprotocol 2.4GHz radio, digital interfaces, ADC, AES encryption, and various crystal oscillators for precise timing. The design also incorporates power management blocks and sensors block for monitoring parameters such as temperature, and humidity. Additionally, a charging block with a Type-C USB port enhances the device's charging capabilities.

The schematic designs detail the connections and configurations of the MCU's pins for power supply, ADC inputs, debug serial, antenna, LED, and crystal oscillators. The flexible PCB layout ensures compatibility with the device's design requirements, while a compact Li-ion battery provides the necessary power supply.

Overall, the project aims to create an ultimate flexible WWD with advanced features and efficient power management, suitable for various applications in healthcare, wearables, and wireless connectivity.

Our design process has guided us through the intricate journey of creating a highly flexible and versatile WWD. We have meticulously planned and examined various aspects of the device, including its hardware components, power supply options, microcontroller pin configurations, sensors, and battery choices. This comprehensive foundation has set the stage for developing an innovative WWD with significant potential.

In the upcoming chapter, we will initiate a comprehensive exploration of the assembly process, elucidating each step and addressing any challenges that may arise.

This in-depth examination will encompass not only the assembly of both the prototype and ultimate versions of the flexible WWD but also a meticulous analysis of the testing procedures.

We will carefully inspect the connections and conduct initial assessments to ensure the proper functionality of these WWDs. By the end of the chapter, we will have gained a solid undersanding of the intricacies involved in the assembly and testing phases.

CHAPTER 3

THE ASSEMBLING PROCESS OF WWD

In this chapter, we will elucidate the processes involved in assembling both rigid PCBs for prototyping WWDs and flexible for the ultimate WWDs, specifically tailored for wound monitoring applications. The precise configuration and fabrication of these PCBs play a pivotal role in ensuring the robustness and functionality of the prototype while meeting the flexibility and durability demands of the ultimate version. We will delve into material selection, layer stack-up, trace routing, and component placement, offering comprehensive insights into the underlying engineering principles that drive the success of these essential components within the domain of wearable health technology.

3.1 Component Assembly for the Prototype WWD on PCB

It is essential to ensure that the PCB is free from any oil, residue, or external substances to initiate the component assembly process on the PCB. We accomplish this by using a contact cleaner to cleanse the PCB meticulously. Following this step, we apply a layer of flux oil to the PCB in preparation for soldering the components, as illustrated in Figure 3.1.

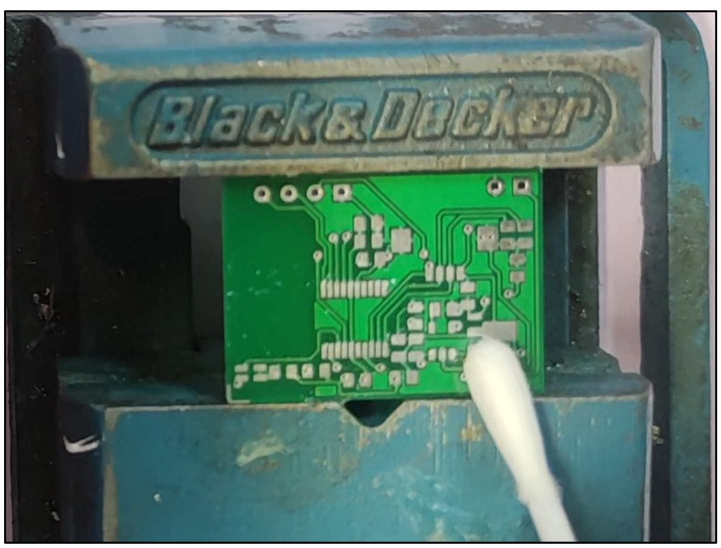

Figure 3.1 PCB surface cleaning process

We begin the soldering process with capacitors and resistors, as their assembly allows for convenient error checking of the routes and connections. After successfully assembling the capacitors and resistors, we proceed to install the charge IC and regulator IC, as shown in Figure 3.2.

We solder one side of each component onto its respective base connection during the assembly process to facilitate easy correction and verification. We solder the remaining side onto the board using a soldering iron or a blower heater at an appropriate temperature once we correctly position all components on their corresponding base connections. We carefully select the temperature to prevent excessive heating of both the components and the PCB.

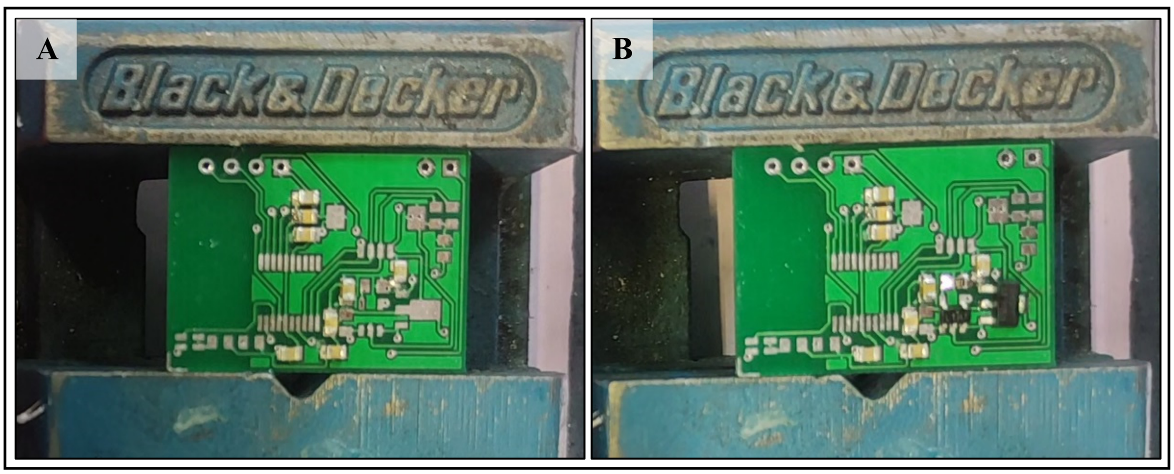

Figure 3.2 Assembly process: (A) capacitors and resistors, (B) charge IC and regulator IC

It is necessary to conduct a voltage check using a 4.5V power supply and a voltmeter prior to assembling the MCU. This check involves verifying both the input voltage and output voltage of both the charge IC and the regulator IC, as depicted in Figure 3.3.

The purpose of this voltage check is to ensure accurate connections and the efficient operation of the components. It is important to note that excessive voltage, exceeding 3.3V, has the potential to harm the MCU. Therefore, performing a voltage check before assembling the MCU is necessary as a precautionary measure.

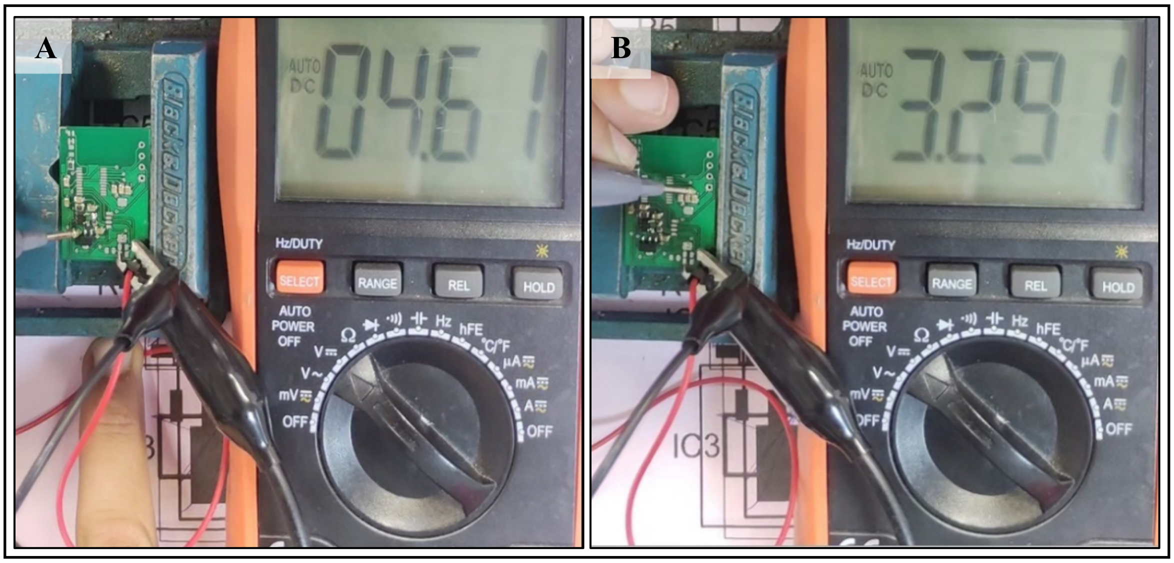

Figure 3.3 Checking (A) input voltage, (B) output voltage of regulator and charge IC

After successfully completing the voltage check, we assemble the MCU with the utmost precision, as illustrated in Figure 3.4.

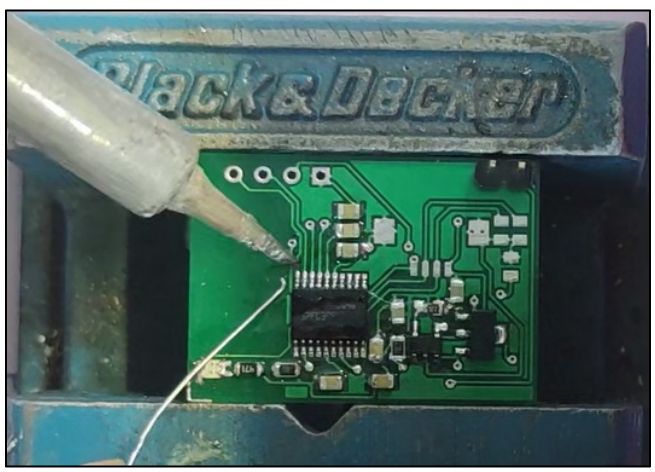

Figure 3.4 MCU assembly

Following this, we should meticulously install the dual LED, comprising both red and green LEDs (Figure 3.5). Due to the LED's plastic composition, we must connect it with great care and at a lower temperature to prevent any damage or mishaps.

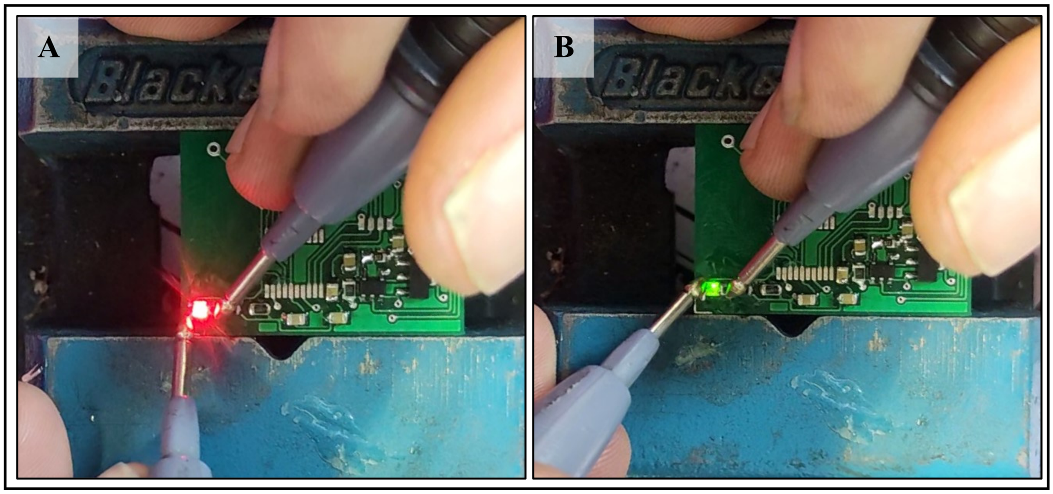

Figure 3.5 Light test for LED (A) red LED, (B) green LED

Next, when we finish soldering the components, we use a heater blower with a temperature set between 370°C to 400°C to ensure that everything is securely attached to the prototype PCB.

We need the HC-05 BLE module itself for assembling; no extra parts or pin headers are required. Therefore, we meticulously detach the HC-05 BLE module from its extra connectors and headers to prepare it for attachment to the prototype PCB.

Afterwards, we carefully solder the HC-05 BLE module onto the backside of the PCB. We need to ensure that we securely connect the functional and crucial pins for the wearable device, as demonstrated in Figure 3.6.

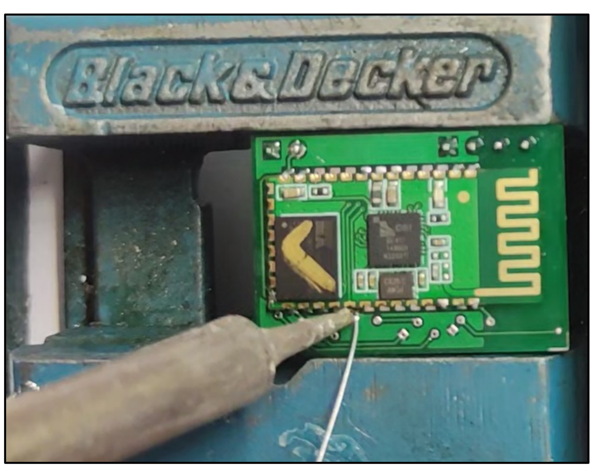

Figure 3.6 HC-05 BLE module assembly

We proceed to conduct error checking on the WWD using an external power supply after completing the assembly of the HC-05 BLE module again. Therefore, the power LED of the HC-05 BLE module starts blinking, indicating that the required connections are functioning efficiently, as shown in Figure 3.7.

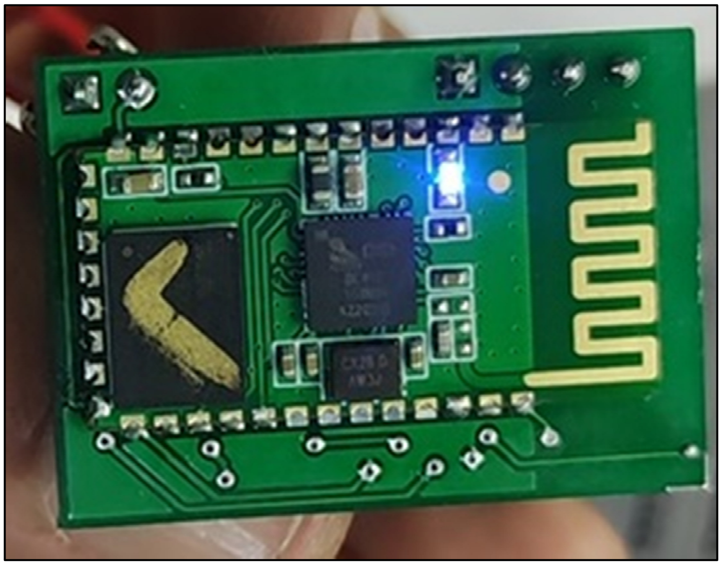

Figure 3.7 HC-05 BLE module assembled and blinked

In the final assembly step, we meticulously install the sensor connector on the PCB, as shown in Figure 3.8. Once again, we verify all the components in their correct positions and check the connections to ensure their conductivity and firmness.

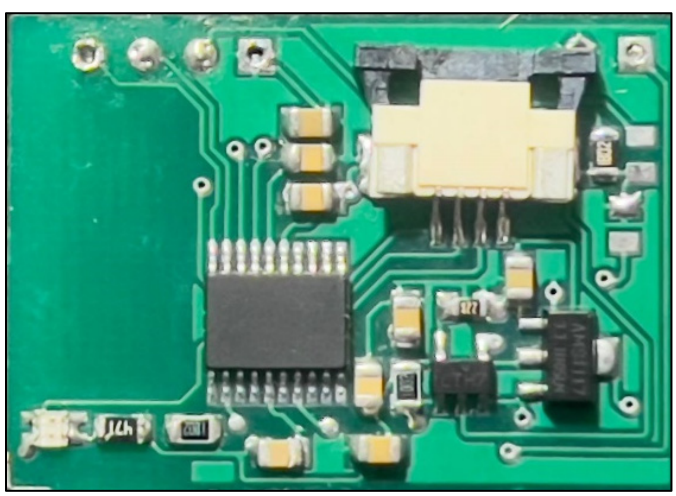

Figure 3.8 Assembled Prototype WWD

Once again, after connecting the sensors to the connector, we use an external power supply to check the voltage of the regulator, MCU, HC-05 BLE module, and sensors. We check the regulator's 3.3V output, ensuring that all component voltages are 3.3V, as shown in Figure 3.9.

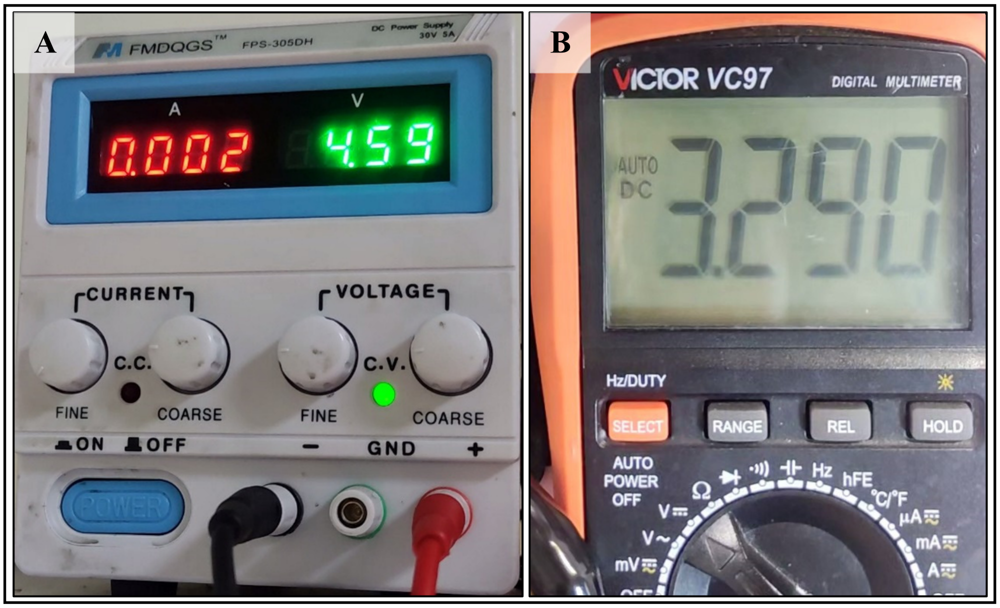

Figure 3.9 (A) Input voltage, (B) voltage of MCU, BLE, and sensors

3.2 Component Assembly for the Ultimate Flexible WWD on PCB

In the process of flexible PCB fabrication, the assembly of components is a critical step, and it is essential to proceed methodically. We begin with the assembly of capacitors and resistors again.

However, when working with polyimide material, caution is paramount. Polyimide is highly sensitive to heat, and excessive heat from soldering irons or heaters can lead to deformation or even burning of the material.

Once we free the flexible PCB from any oil, residue, or extraneous material and coat it with flux oil, we meticulously assemble the capacitors and resistors.

Following this, we carefully add the crystals and ICs to the board. The ultimate result is the fully assembled flexible WWD, as illustrated in Figure 3.10.

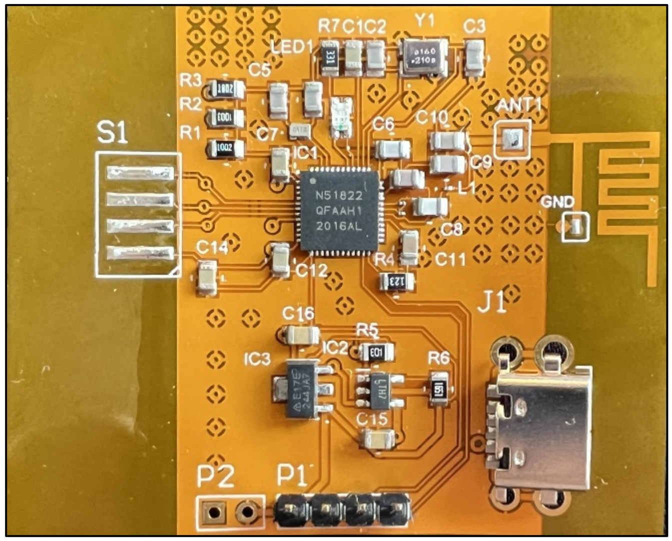

Figure 3.10 Assembled flexible WWD

3.3 Debugging and Programming the MCU for the WWD

The MCU undergoes debugging and programming using STM32CubeIDE (Version 1.13.2, 2023), STM32Cube Programmer (Version 2.14.0, 2023), and STM32CubeMX (Version 6.9.2, 2023) software. These software tools, recommended by the manufacturer, facilitate the debugging and programming process of the MCU using C++ coding.

In this chapter, we delve into the crucial processes of assembling both rigid and flexible PCBs for WWDs, with a specific focus on wound monitoring applications. The meticulous configuration and fabrication of these PCBs are vital to ensuring the prototypes' robustness and the flexibility and durability required for the final versions.

We covered material selection, layer stack-up, trace routing, component placement, and the underlying engineering principles guiding wearable health technology.

This chapter thoroughly explores the assembly of wearable devices, from initial PCB fabrication to component assembly. It highlights the challenges and considerations in working with polyimide material, emphasizing the significance of meticulous work to ensure proper functionality. The chapter concludes with the fabrication of the flexible PCB, meeting specific requirements and standards.

In the next chapter, we will conduct experiments to evaluate the functionality and resilience of the wearable device, even in adverse conditions. These experiments will provide valuable insights into the device's performance and its potential in real-world scenarios, bringing us closer to the practical application of our innovative wearable technology.

CHAPTER 4

EXPERIMENTS AND RESULTS

Various factors, such as temperature and humidity, affect the likelihood of a wound becoming infected. It is important to note that wound infections can occur across a wide range of conditions. Healthcare organizations provide general guidelines based on the information presented below (WHO, 2016):

- Temperature: The World Health Organization (WHO) states that the optimal temperature for wound healing is approximately 37°C, which is the normal body temperature. While wound infections can happen in various temperature ranges, higher temperatures (above 37°C) can create a more conducive environment for bacterial growth and the development of infections.

- Humidity: Maintaining relative humidity levels around 40% to 60% is generally considered beneficial for wound healing. This range helps to ensure an appropriate level of moisture around the wound, supporting the body's natural healing processes. Extremely dry or excessively moist conditions can potentially impede wound healing and increase the risk of infection.

Wound healing is a multifaceted process influenced by several factors, including an individual's overall health, the type of wound, and any underlying medical conditions. Proper wound care, hygiene, and adherence to the advice of healthcare professionals are crucial in minimizing the risk of infection and fostering successful wound healing (WHO, 2016).

In this chapter, we delve into an exploration of the functional capabilities and resilience of our flexible WWD under various simulate conditions that patients may encounter during wound monitoring. We focus our experimentation on the application of the flexible WWD for monitoring wounds on the hand. For this purpose, we have meticulously designed a prototype case tailored to the device's flexibility. It is worth noting that the design of the case can be adapted to accommodate variations in wound types and locations on the body.

To conduct our experiments, we have developed a custom-made chamber that allows us to simulate diverse environmental conditions, specifically varying temperature and humidity levels. Through controlled simulations, we aim to assess the device's performance and durability in scenarios that may influence its functionality during real-world wound monitoring scenarios.

Our analytical approach involves comprehensive data collection, including the capture of oscilloscope readings, enabling us to figure out the unique roles and responsibilities of each component within the flexible WWD. This in-depth analysis will provide valuable insights into the device's behavior and responses under different conditions, contributing to a more robust understanding of its practical applications in the field of healthcare technology.

4.1 The Flexible Prototype Case for the WWD

In order to monitor a patient's wound with the WWD effectively, it is crucial to create a casing that is not only practical but also user-friendly. This casing should be flexible to provide to the patient's needs. Therefore, we decide to use a sponge rubber prototype housing. The thickness of this sponge rubber allows us to incorporate the flexible board, battery, and Type-C USB easily, as shown in Figure 4.1.

Figure 4.1 Casing design for the flexible WWD

We implant the sensors on the inner surface of the sponge rubber to provide coverage for a wound, as depicted in Figure 4.2.

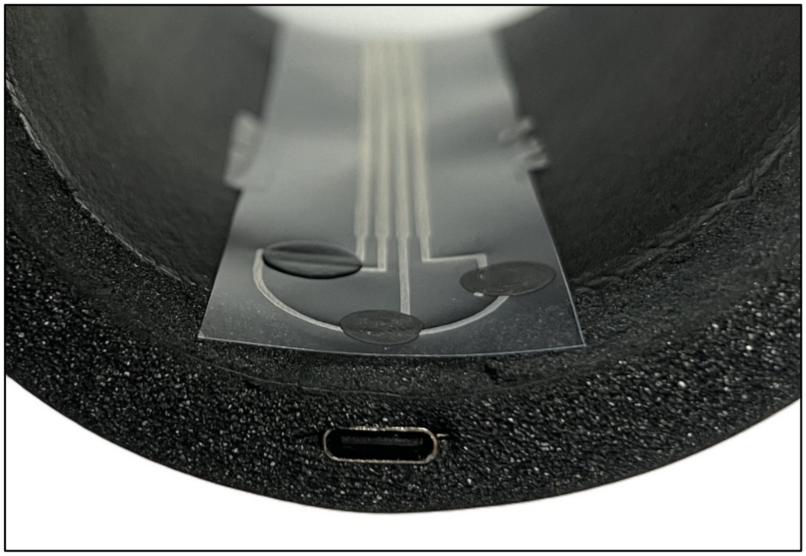

Figure 4.2 Sensors embedded within the inner surface of case

As previously discussed, we have developed a flexible casing specifically designed for monitoring hand wounds, illustrated in Figure 4.3. However, it is important to note that this design is adaptable to accommodate various wound types and their locations on the patient's body. Furthermore, we can substitute the casing material with other flexible materials suitable for wearable devices.

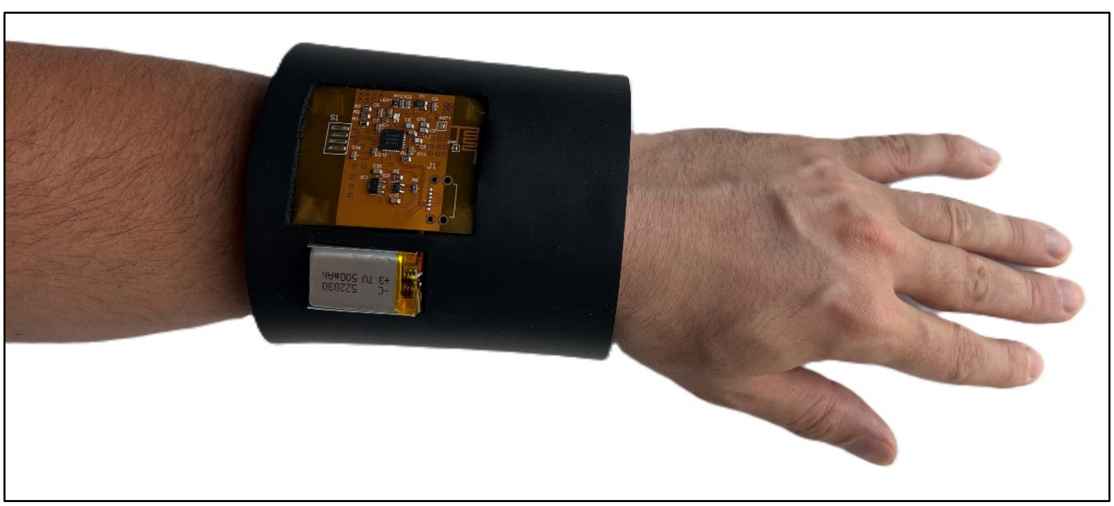

Figure 4.3 Prototype casing designed for monitoring hand wounds

4.2 Simulating Temperature and Humidity Variations

The Flexible WWD plays a crucial role in monitoring temperature and humidity variations, transmitting this data via BLE to a smartphone. This information allows patients to assess their wound's condition and determine the optimal time for bandage replacement. Hence, our WWD must demonstrate durability in the face of temperature and humidity fluctuations to ensure accurate sensor readings. We construct a custom chamber to evaluate its robustness, as illustrated in Figure 4.4, equipping it with adequate valves, input/output conduits for controlling heat and moisture, and the necessary cabling.

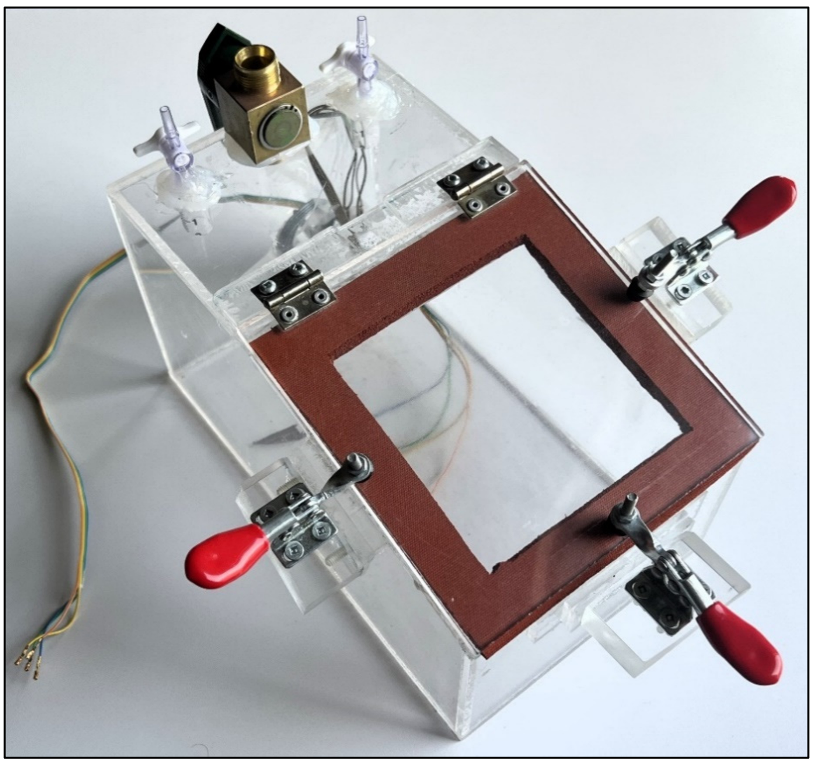

Figure 4.4 Custom made chamber

Concerning the chamber design showcased in Figure 4.4, we have incorporated a door featuring three dependable latch locks. Moreover, we have integrated three valves to control the flow of temperature and humidity in and out of the chamber once we securely fasten the door with the latch locks. Additionally, for seamless operation even with the door closed, we have employed four-pair flat wires to connect the wearable device to the exterior of the chamber in specific scenarios.

4.3 Design Electrodes and Resistance of Sensors

We have meticulously engineered the electrodes of the sensors to facilitate connectivity, allowing them to be effortlessly linked using a versatile medium such as carbon tape or any form of conductive adhesive tape, to the designated port "S1," as illustrated in Figure 4.5.

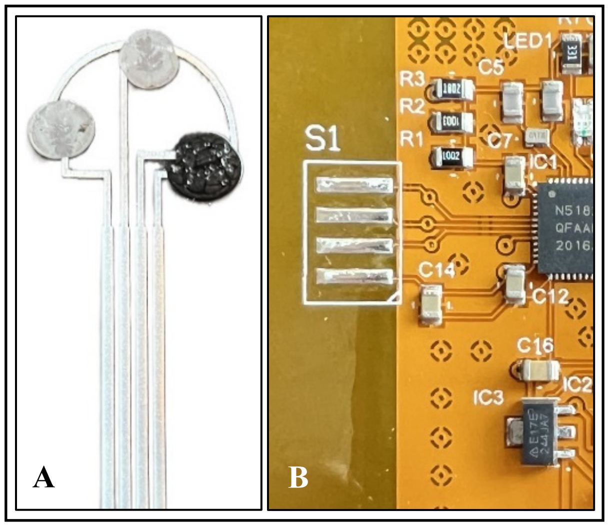

Figure 4.5 (A) Designed sensor,
(B) Sensor connector

The temperature and humidity sensors are analog and have been developed and published by the lab of Professor Ricardo Izquierdo. The temperature sensor, as outlined by (A. A. Shboul, A. Gohel, M. Ketabi, & R. Izquierdo, 2023), is utilized as the disposable temperature sensor. Additionally, the humidity sensor, described by (M. Ketabi, A. Al Shboul, S. Mahinnezhad, & R. Izquierdo, 2021), is employed as the disposable humidity sensor in the design of the sensor block for the wearable device. Technical specifications of the temperature and humidity sensors are presented in Table 4.1.

Table 4.1 Sensors specifications A. A. Shboul et al. (2023, p. 3), M. Ketabi et al. (2021, p. 2)

Sensors	Resistance in ambient air	Operational range
Temperature	150 KΩ ~ 200 KΩ	20°C ~ 80°C
Humidity	200 KΩ	30% ~ 90%

These sensors display instability, lack standardization, have varying ranges of resistance (as depicted in Figure 4.6), and differ from one another. Table 4.2 provides information on the diverse resistance ranges of the sensors.

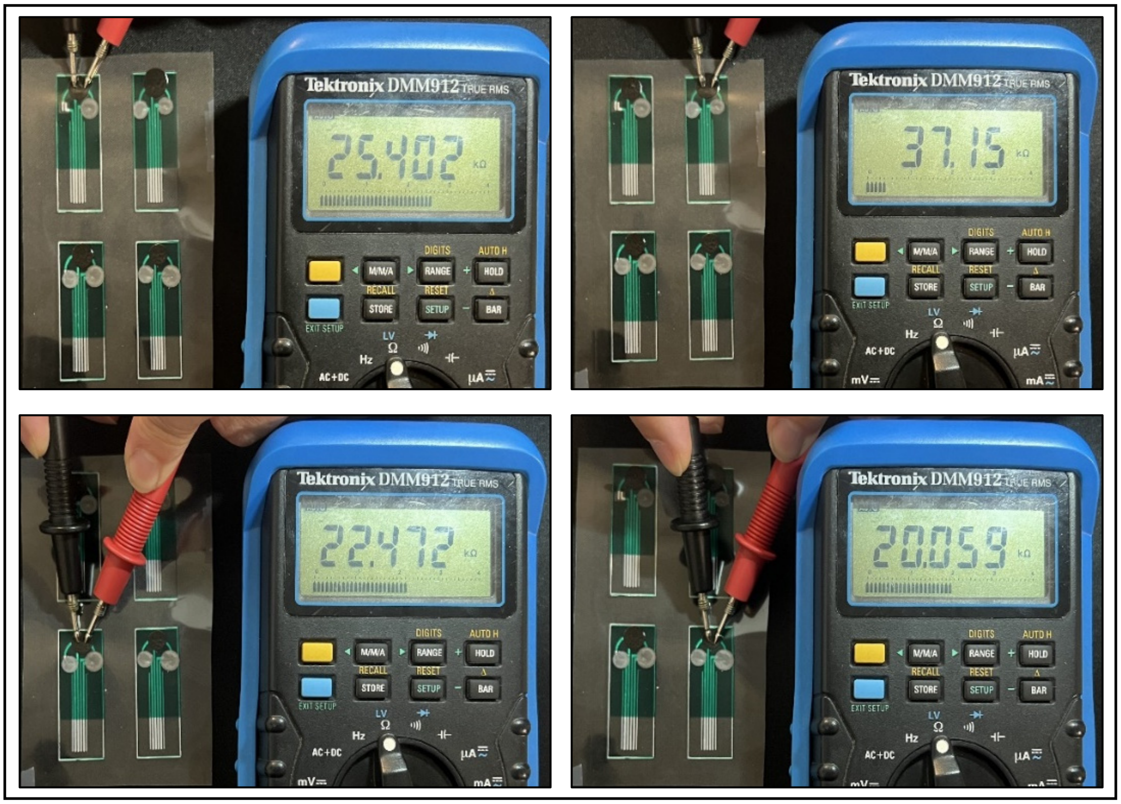

Figure 4.6 Different resistance of sensors

Table 4.2 Diverse resistance ranges of the sensors in reality

Resistance / Sensors	Min. Ω	Max. Ω
Temperature	~17K	~1M
Humidity	~50K	~250K

We designed a voltage dividing system in the sensor block, incorporating a constant resistor and a variable resistance sensor. The ADC channels receive variable voltage from the sensors by adjusting the sensor's resistance and convert them to digital signals; they do not calibrate the signals to produce understandable data.

Calibration is necessary to ensure interpretable data on the smart device. This involves programming the MCU and comparing the real data with the sensed data. This calibration needs to be performed each time a new sensor is replaced. Notably, when using a standardized sensor with constant resistance, we only need to calibrate the received data once.

4.4 The Flexible WWD Operation

Once we program the MCU, connect the sensors, and turn on the WWD, the regulator provides 3.3V for the sensors, and the WWD begins transmitting the initial voltage difference sensed by the sensors. The sample voltage of sensors in ADC channels are shown in Figure 4.7.

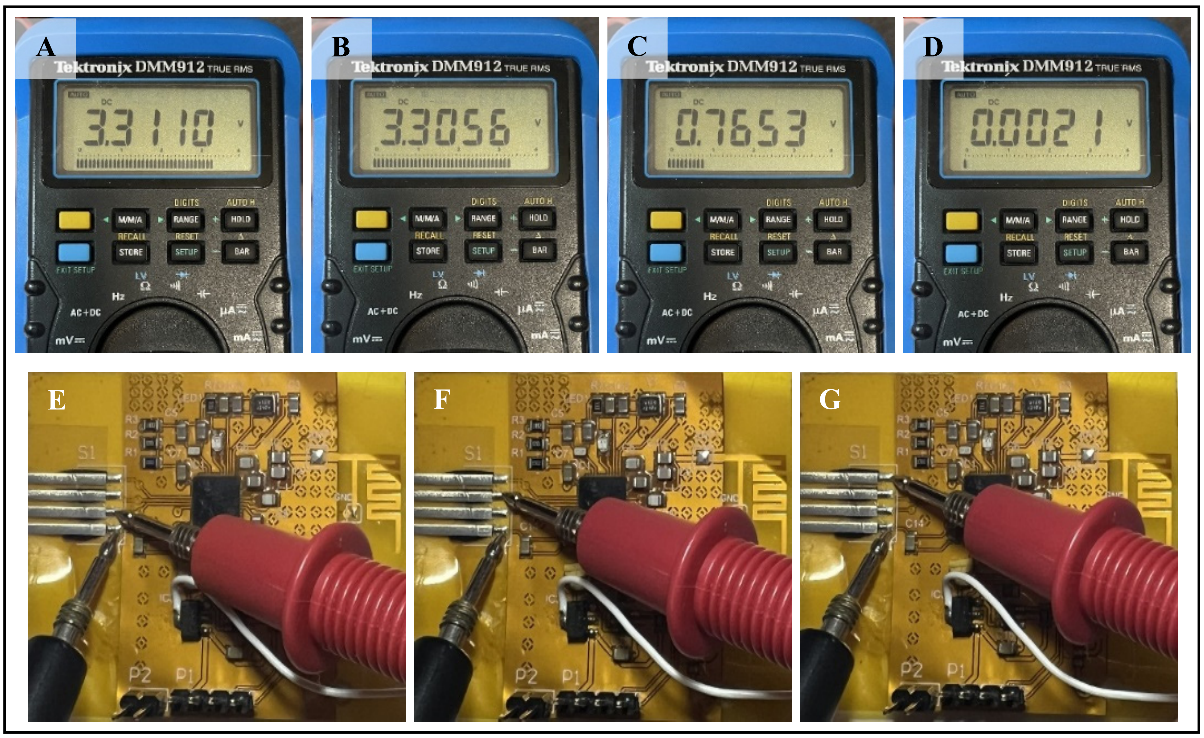

Figure 4.7 (A) Output voltage regulator, (B, E) reserved sensor voltage, (C, F) humidity sensor voltage, (D, G) temperature sensor voltage

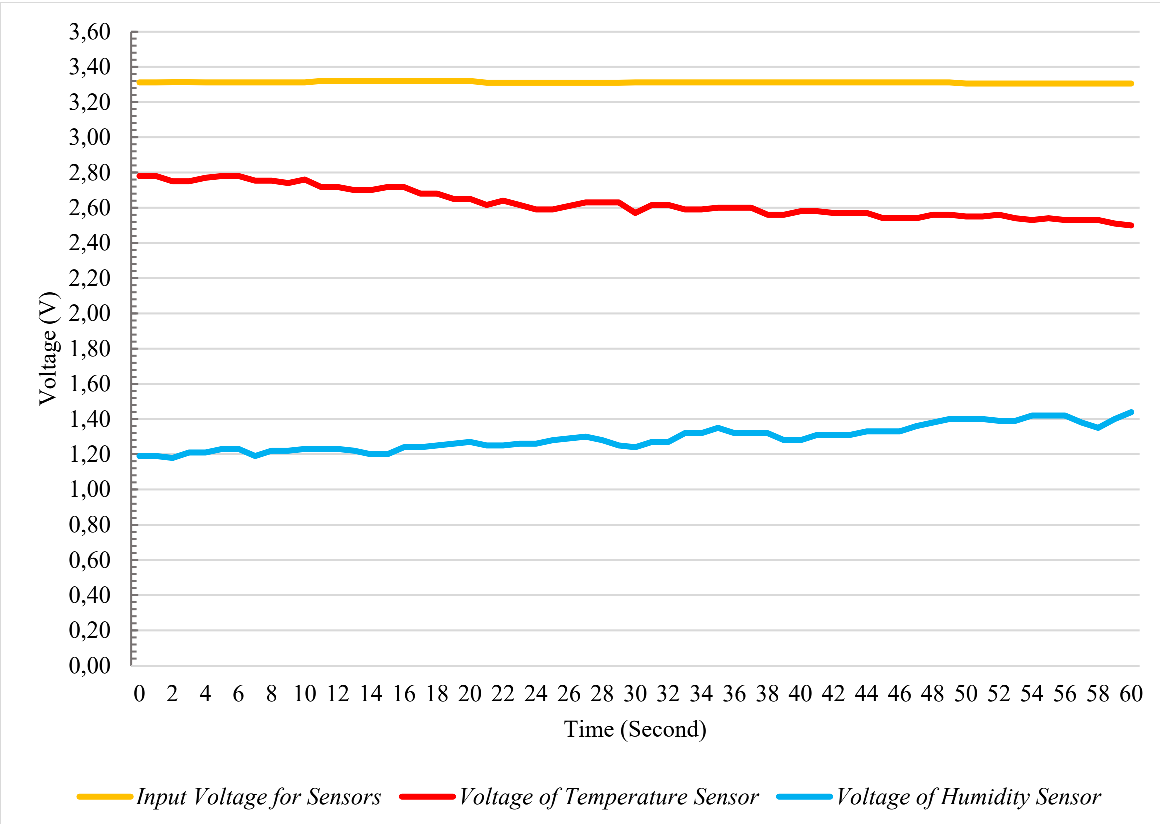

Figure 4.8 Voltage diagram of sensors block

Figure 4.8 displays the regulated input voltage of 3.3V for the sensors block. Furthermore, the design incorporates voltage division for the sensors block, illustrating their analog voltage in the same figure. The MCU's ADC channels measure these slight changes in the analog voltage of the sensors, subsequently converting them to digital before transmitting the data.

However, these values are not immediately comprehensible, as they undergo analog-to-digital conversion through ADC channels before being transmitted to the smart device by the MCU. Calibration process is required to make these values understandable. This involves adding supplementary code to the MCU's existing code to ensure the values are interpretable.

Figure 4.9 illustrates the initial values acquired from the sensors, which are subsequently transmitted to the smart device. These values result from the voltage division occurring between the sensors and the integrated resistors within the sensors block.

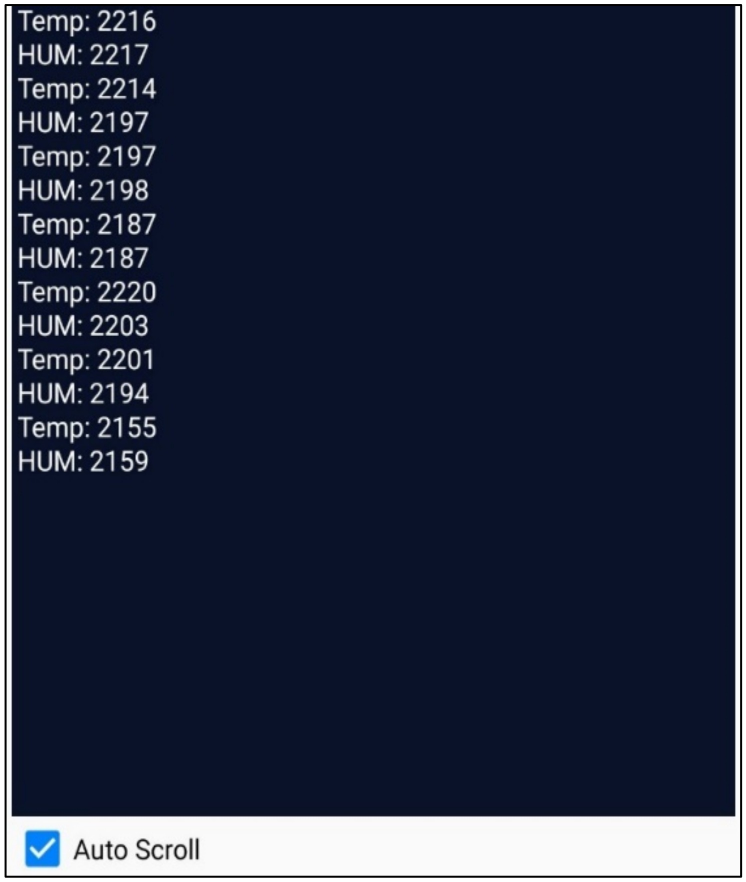

Figure 4.9 Initial sensor data transmitted by WWD

We use a thermometer to measure the real ambient temperature and humidity values precisely. Subsequently, we modify the programming code to ensure that the sensors provide accurate numerical data reflecting these real-world values.

Once we integrate specific calibration code into the MCU's programming and restart the flexible WWD, the second set of values became understandable. These calibrated values, as shown in Figure 4.10, are now clear and interpretable.

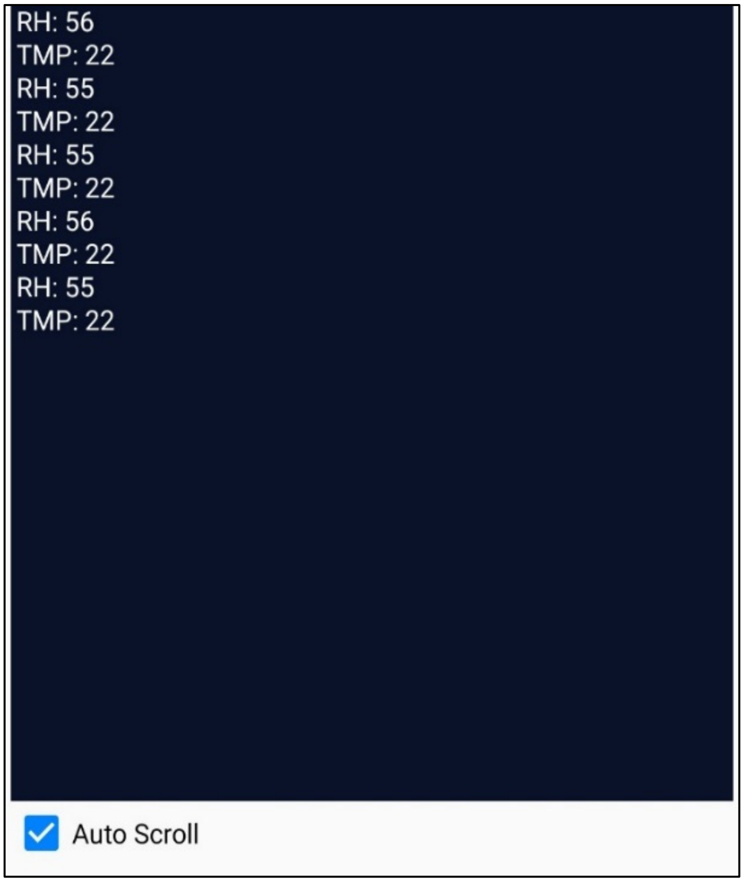

Figure 4.10 Calibrated sensor data transmitted by WWD

4.5 Durability Simulation

We are conducting a simulation to assess the performance and resilience of the flexible WWD under varying temperature and humidity conditions. As mentioned before, the human body maintains a temperature of around 37°C, with ambient humidity levels ranging from 40% to 60%.

In this simulation, we intentionally manipulate the temperature and humidity levels within a controlled custom chamber. Our aim is to evaluate the durability of the flexible WWD when subjected to extreme high and low temperatures and humidity, as well as rapid fluctuations in these environmental parameters.

During the simulation, the wearable device is set to monitor temperature and humidity values at one-minute intervals over a span of six hours. Throughout this experiment, we closely observe and analyze the sensor data, which is subsequently transmitted to a connected smart device.

Our primary focus is to detect any variations in the sensor readings caused by the deliberate alterations we make to the chamber's temperature and humidity settings. We have presented the temperature and humidity data from the simulation separately in Figures 4.11 and 4.12 to provide a more comprehensive overview.

4.5.1 Temperature Durability Simulation

We place the flexible WWD and a thermometer inside the customized chamber to use the thermometer data as the reference temperature to assess its resilience to temperature fluctuations. We artificially modifying the ambient temperature for a period of six hours. Throughout this period, the device consistently relay the ambient temperature measurements to the paired smart device.

After the initial ambient temperature exposure lasting for forty minutes, we implement a gradual temperature increment within the chamber. This increment lead to a corresponding rise in temperature values displayed on the smart device, ultimately reaching an approximate temperature of 41°C, achieved by heating the chamber's interior.

The wearable device remains within this elevated temperature environment for an additional two hours, enabling us to conduct a thorough assessment of its performance and durability under high-temperature conditions. Throughout this extend duration; the wearable device demonstrate remarkable consistency and efficiency in transmitting temperature data, as evidenced by the data in Figure 4.11.

Thereafter, we commence a controlled temperature reduction phase, initiating a process where the WWD sense and transmit lower temperature values to the smart device. As anticipated, the temperature readings on the smart device begin to show a visible decline, indicating the device's responsiveness to temperature fluctuations.

We replicate this experiment multiple times, with each repetition consistently yielding analogous results. Figure 4.11 represents one sample of data from the flexible WWD. These successful trials underscore the device's ability to adapt promptly to temperature variations, ensuring the accurate transmission of updated temperature values.

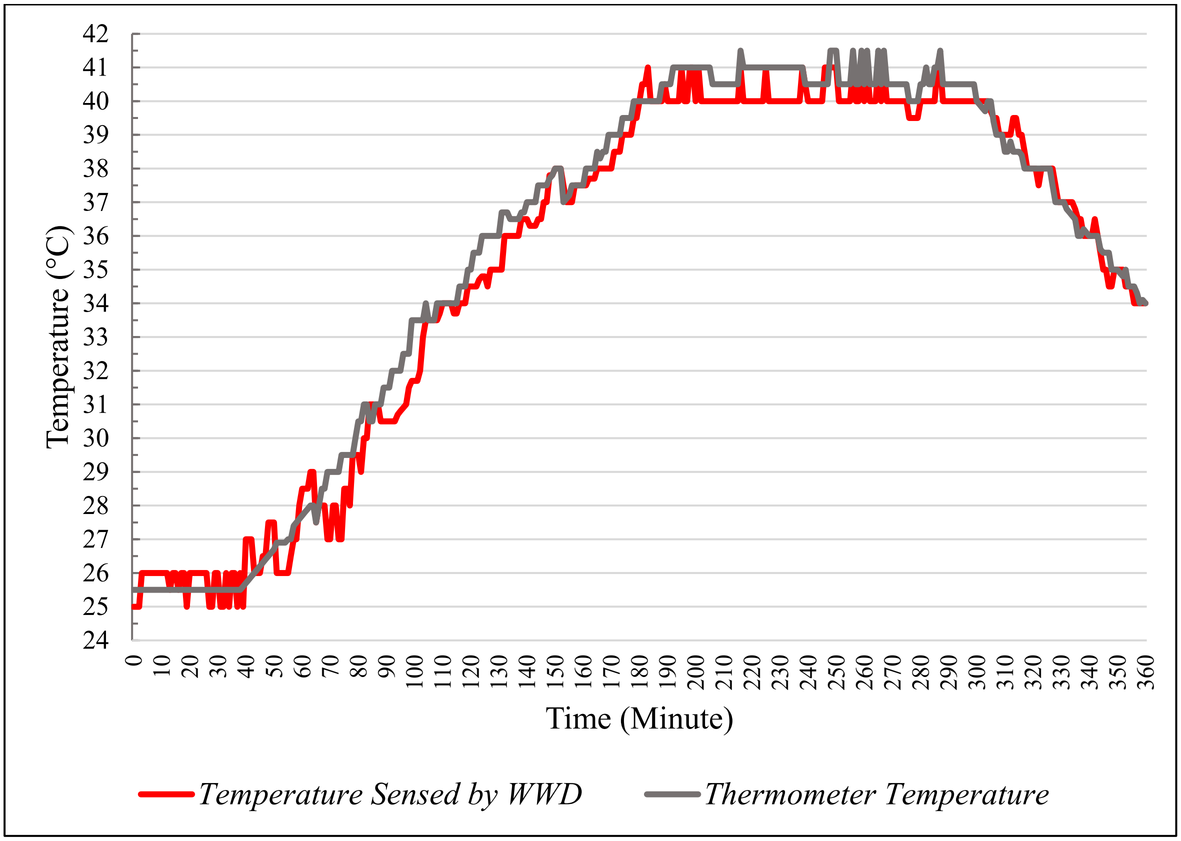

Figure 4.11 Temperature sensed by WWD during temperature variations

4.5.2 Humidity Durability Simulation

We conduct an experiment similar to the temperature durability simulation to evaluate the WWD's resilience to humidity fluctuations. In this simulation, we place the flexible WWD and a hygrometer inside the custom chamber and deliberately manipulate the humidity levels for a period of six hours. Throughout this duration, the device consistently detects and transmits precise humidity measurements to the connected smart device while we monitor the hygrometer data as the reference for the humidity of the chamber.

We initiate a gradual increase in humidity levels by introducing cold steam into the chamber after the initial forty minutes, raising the humidity to approximately 70%. This lead to a corresponding increase in moisture values displayed on the smart device. The WWD continues to operate within this elevated humidity environment for an additional two hours, enabling us to evaluate its performance and durability under high-humidity conditions. Throughout this duration, the WWD consistently and effectively transmit humidity data (Figure 4.12).

Thereafter, we evacuate the moisture of the chamber, causing the WWD to update and transmit the lower humidity values to the smart device. As anticipated, the humidity readings on the smart device begin to decrease visibly.

We conducted this experiment multiple times, and each iteration yielded consistent results, confirming the device's ability to promptly respond to humidity fluctuations and accurately transmit the updated values.

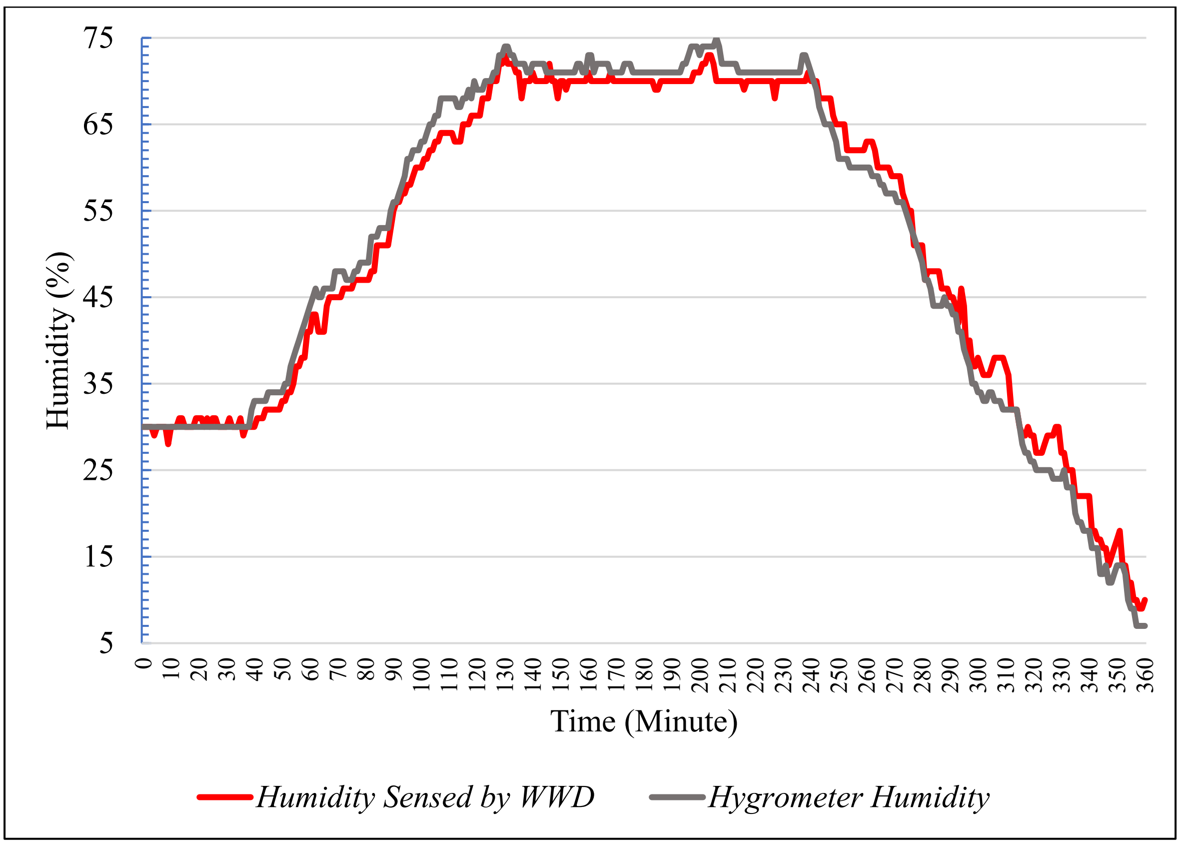

Figure 4.12 Humidity sensed by WWD during humidity variations

4.6 Bending and Deforming the WWD for Durability Testing

We purposely expose the flexible board to bending and deformation, simulating possible unintentional actions by a user, to assess the robustness of the flexible WWD during regular operation and data transmission.

As per our design specifications, we employ the AZ1117 regulator IC to maintain a stable output voltage of 3.3V for the MCU and various components within our WWD, regulating the input voltage range of 4.2V to 6.5V.

Figure 4.13 displays the utilization of a power supply with an input voltage of 4.28V for the regulator IC. Notably, Figure 4.13 illustrates the absence of any resonance at the input of the regulator IC.

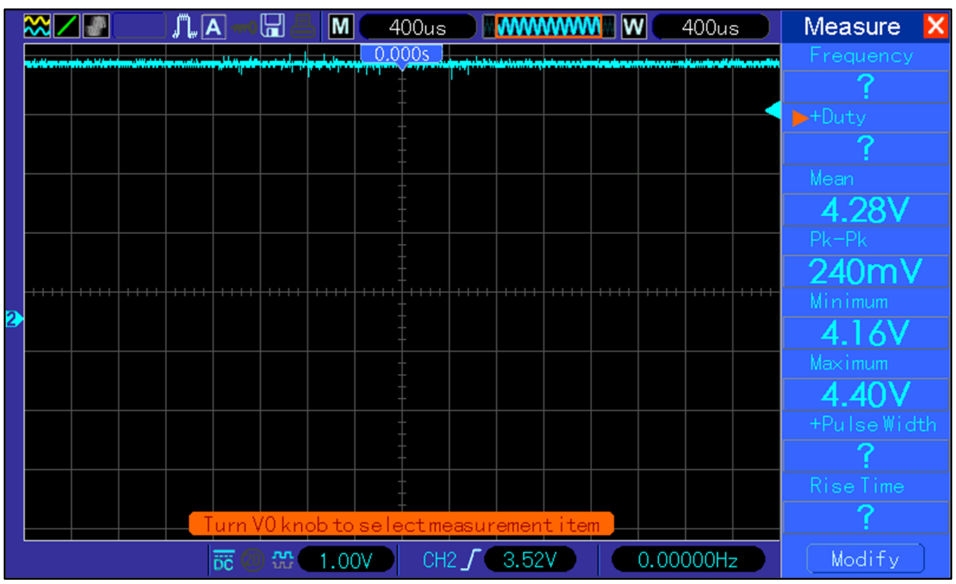

Figure 4.13 Input voltage analysis of regulator IC

When the flexible WWD remains in its unbent and undistorted state, as illustrated in Figure 4.14, the output voltage consistently measures around 3.6V with no observable resonance. This stability in the output voltage is crucial for ensuring the proper functioning and performance of the device under normal and non-stressful conditions. It guarantees that the wearable device can effectively power its components and maintain reliable data transmission without any significant fluctuations or disruptions. This level of voltage stability is essential for achieving the desired performance and accuracy in patient monitoring and data collection.

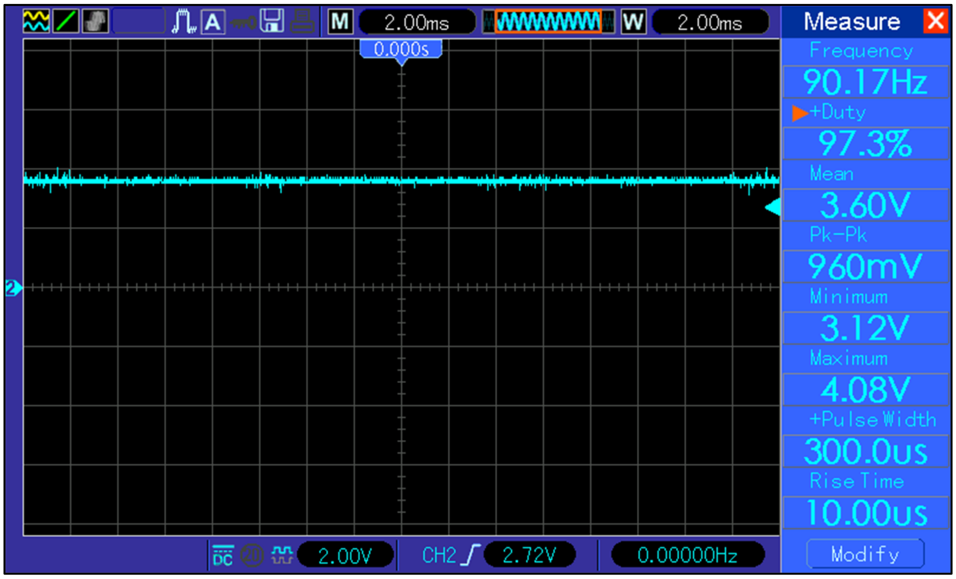

Figure 4.14 Output voltage analysis of regulator IC

When intentionally subjecting the flexible WWD to bending, we face limitations due to the assembly of rigid components on the polyimide PCB and the numerous connections with soldering. Consequently, we cannot bend it very hard. Nevertheless, as illustrated in Figure 4.15, this degree of bending is considered reasonable, as it aligns with our objective to monitor wounds on the patient's hand.

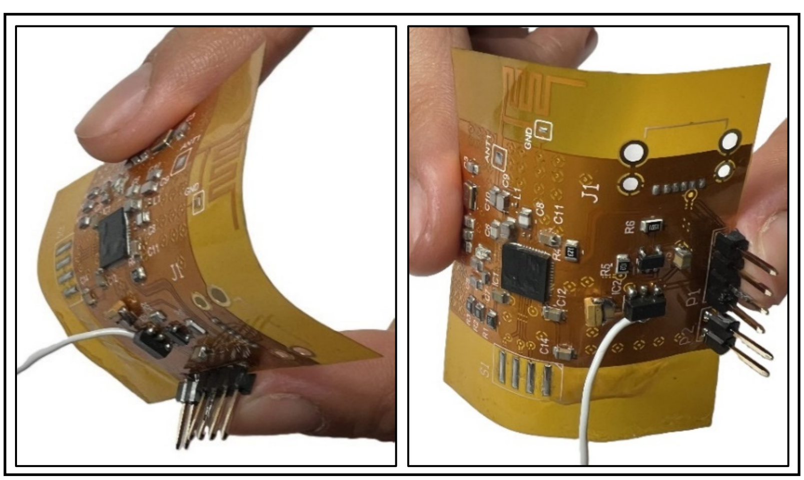

Figure 4.15 Bend shape of flexible WWD

During the bending, we notice a slight resonance at the output of the regulator IC, as depicted in Figure 4.16. Notably, even with these deliberate deformations, the average output voltage remains stable at approximately 3.56V, which falls within an acceptable range.

What is truly remarkable is that throughout these controlled maneuvers, the device continued to operate flawlessly, ensuring uninterrupted data transmission and consistently delivering precise results. Table 4.3 provides related information.

Table 4.3 Regulator variations during board bending

Voltage of Regulator	Frequency (Hz)	Voltage (V)	Min. ~ Max. (V)
Input	-	4.28	4.16 ~ 4.40
Output	90.17	3.6	3.12 ~ 4.08
Output during board bending	13.29	3.56	3.12 ~ 4.20

This exceptional performance under conditions of physical stress demonstrates the device's robustness and reliability in real-world scenarios where patients might inadvertently subject it to bending or deformation. The ability to maintain stable power output and data transmission even in such situations is a testament to the device's suitability for long-term, everyday use in healthcare and patient monitoring applications.

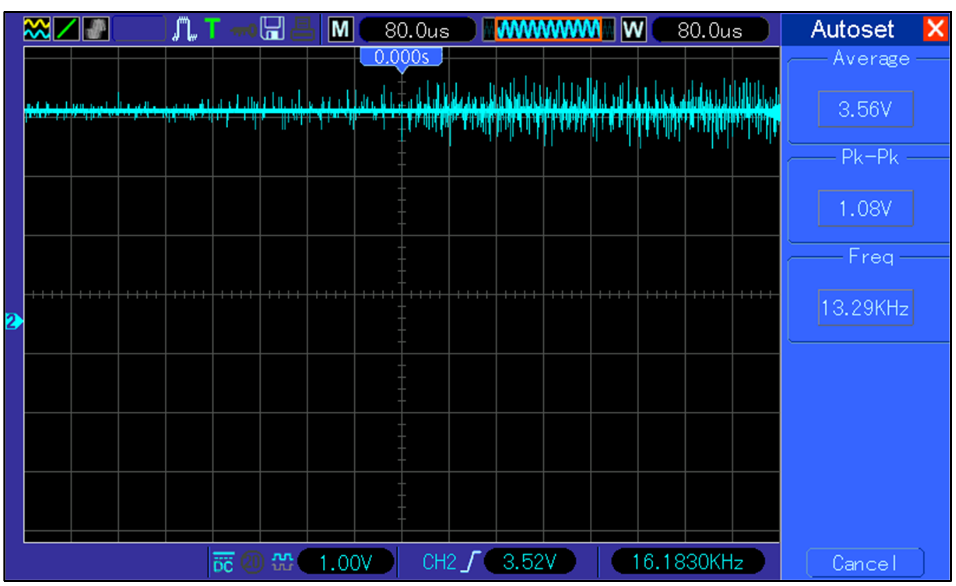

Figure 4.16 Regulator IC output during flexible board bending

4.7 BLE Voltage Consumption and Stability During Data Transmission

When we establish a connection between the WWD and a smart device via BLE, the input voltage supplied to the MCU remains consistently stable. As illustrated in Figure 4.17, this input voltage matches the output voltage of the regulator IC, maintaining a constant value of 3.56V.

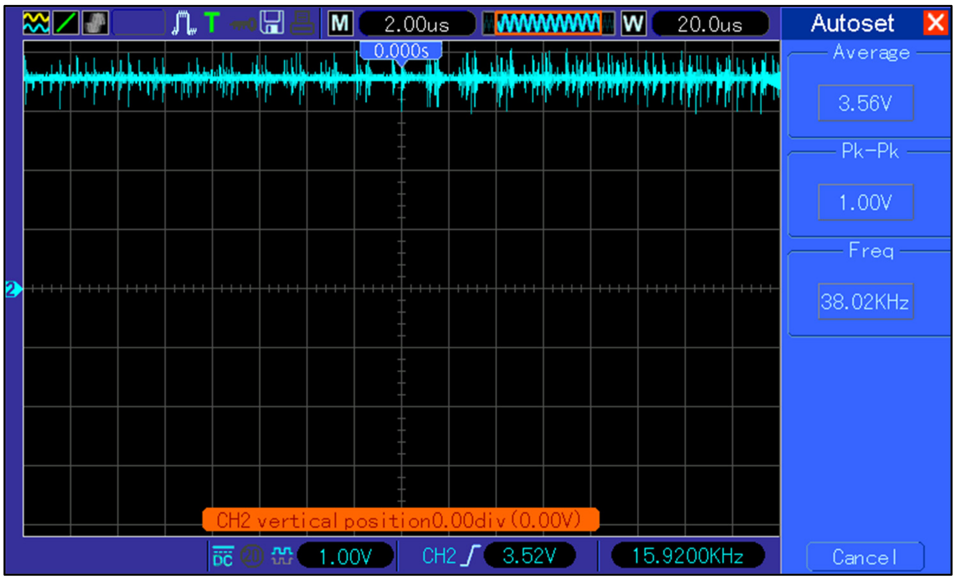

Figure 4.17 Input voltage analysis of the MCU while using BLE

During the process of data transmission and the operation of other device components, we observe minimal resonance in the input voltage of the MCU. However, this resonance, as depicted in Figure 4.17, has such minor significance that we can consider it negligible. Furthermore, it does not affect the stability of the input voltage. Table 4.4 provides related information.

Table 4.4 MCU variations during using BLE

Title	Frequency (Hz)	Voltage (V)	Voltage (V) Pk-Pk
MCU specification	38.02	3.56	1

Most notably, the data transmission process proceed without any interruptions, and the device consistently delivers accurate results. This resilience to minor resonance and the unwavering stability of the input voltage underscore the robustness and reliability of our flexible WWD during real-world usage scenarios, ensuring uninterrupted data communication and precise information dissemination between the wearable device and the smart device.

4.8 Analysis of the RTC Crystal

The RTC serves a multitude of critical functions. Its primary role is to meticulously track the current time, encompassing hours, minutes, seconds, and often even the date and day of the week. This functionality is indispensable for applications that demand precise timing, task scheduling, or event timestamping. RTC modules empower the MCU to execute tasks and events at predetermined times or intervals, offering a robust foundation for applications such as data logging. In these scenarios, the RTC generates timestamps for recorded data, proving invaluable in domains like environmental monitoring, and scientific experiments.

Moreover, MCUs strategically employ RTCs to optimize power management. These controllers can gracefully slip into low-power sleep modes and resurface at scheduled intervals, effectively curbing overall power consumption.

RTC modules also play a pivotal role in data synchronization. They orchestrate the timing of data transmissions, ensuring that data is sent or received at precisely specified times. This feature becomes particularly pivotal in applications like IoT devices, where data synchronization holds paramount importance.

RTCs even offer clock calibration capabilities, safeguarding the accuracy of timekeeping across extended durations. Additionally, these RTCs often assume the roles of timers and counters, facilitating various timing-related operations within an MCU.

For our flexible WWD, the proper functioning of the RTC has paramount significance. By scrutinizing the voltage signals at the RTC ports, as elucidated in Figure 4.18, we can affirm that the RTC crystal harmoniously synchronizes the components of our flexible WWD. This synchronization ensures that the device accurately senses and transmits data at the precise moments required for seamless operation. Table 4.5 provides related information.

Table 4.5 RTC crystal variations

Title	Frequency (Hz)	Voltage (V)	Voltage (V) Pk-Pk
RTC crystal specification	96.15	0.88	0.552

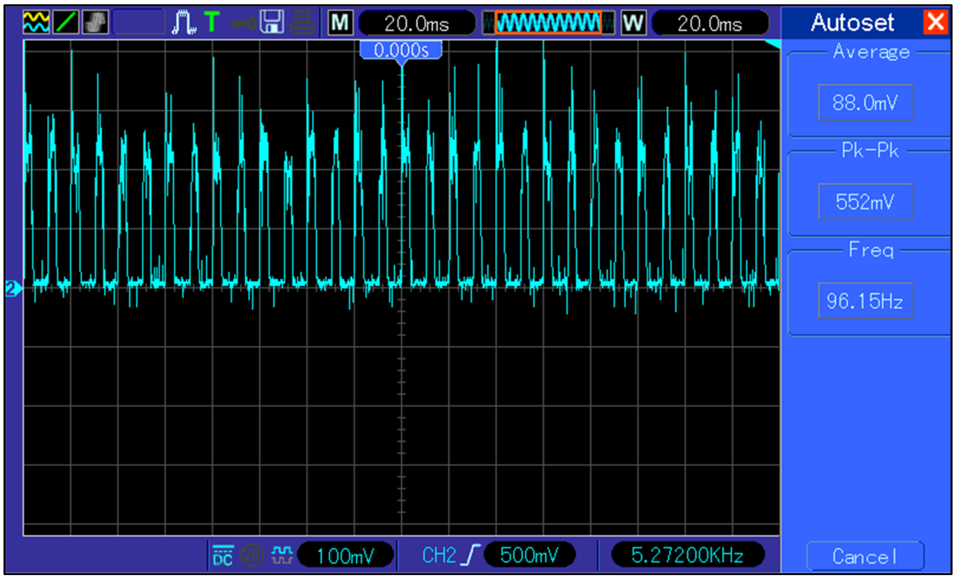

Figure 4.18 Signal voltage analysis of the RTC crystal

4.9 Analysis of the Oscillator Crystal

Oscillator crystals and RTC serve different purposes in electronic devices like our WWD, which require both for specific functionalities. Oscillator crystal is typically used as a clock source for the MCU in our device. It provides a stable and accurate clock signal that enables the MCU to perform various tasks and operations at precise intervals. It ensures that the MCU runs at a specific clock frequency, which is crucial for accurate timing in tasks like data sampling, data processing, and communication with other devices.

RTC crystal, on the other hand, is specifically dedicated to keeping track of time independently of the MCU's clock. It serves as a real-time clock/calendar for our device. RTCs are designed to provide accurate time and date information even when the MCU is in a low-power or sleep mode or when the device is powered off. This is essential for functions like time-stamping data, scheduling tasks, and maintaining an accurate record of events over extended periods.

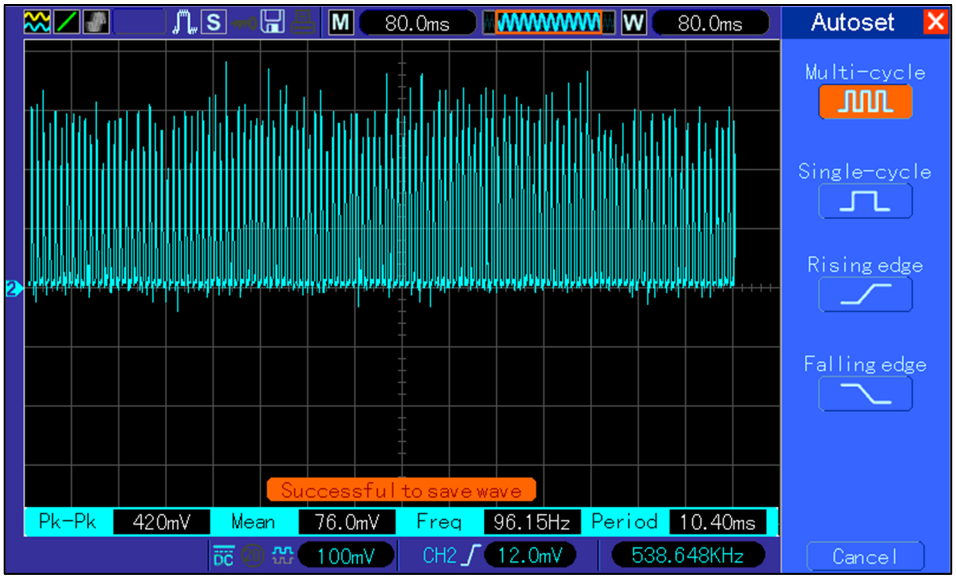

Figure 4.19 Signal voltage analysis of the oscillator crystal

While the oscillator crystal ensures that the MCU operates at a stable clock frequency for general processing tasks, the RTC crystal is responsible for maintaining accurate timekeeping and allowing your device to track time even when it is not actively processing data. Having both crystals in our WWD allows it to perform tasks that require precise timing and time-related functions effectively. Figure 4.19 illustrate the voltage signals of the oscillator crystal in our WWD. Table 4.6 provides related information.

Table 4.6 Oscillator crystal variations

Title	Frequency (Hz)	Voltage (V)	Voltage (V) Pk-Pk
Oscillator crystal specification	96.15	0.76	0.42

This chapter has delved into the multifaceted aspects of our flexible WWD and its resilience in various simulated conditions relevant to patient wound monitoring. We have explored crucial factors such as temperature and humidity, which play pivotal roles in wound infection risk. Understanding these environmental parameters is essential for optimizing wound care.

The chapter began by highlighting the significance of maintaining optimal temperature and humidity levels for effective wound healing. It emphasized the importance of adhering to general guidelines provided by healthcare organizations, which recommend specific ranges for these parameters. Temperature and humidity directly affect wound healing, making them critical considerations in patient care.

Thereafter, we presented the flexible prototype case designed for our WWD. This case, constructed from sponge rubber, is adaptable to different wound types and body locations. It provides a practical and user-friendly solution for monitoring wounds effectively, ensuring patient comfort and convenience.

Our experiments involved the construction of a custom chamber that allowed us to simulate diverse temperature and humidity conditions. This chamber facilitated controlled simulations that closely mimic real-world scenarios. Through these experiments, we assessed the device's performance and durability under conditions that may influence its functionality during actual patient monitoring.

We explored the device's performance under temperature variations, demonstrating its resilience to both high and low temperatures. The experiments displayed its ability to adapt to temperature fluctuations while maintaining accurate data transmission, a vital attribute for successful wound monitoring.

In parallel, we evaluated the device's response to humidity fluctuations, demonstrating its ability to withstand high humidity conditions and promptly transmit data. These findings underscore the device's reliability in various environmental scenarios.

Data collection was a fundamental part of our analytical approach, with oscilloscope readings providing insights into the individual components' roles within the flexible WWD. This comprehensive analysis offered valuable insights into the device's behavior and responses under varying conditions, contributing to a deeper understanding of its practical applications in healthcare technology.

Bending and deforming tests provided further insights into the WWD's durability and reliability during regular operation and data transmission. The device exhibited remarkable stability and consistent performance even when subjected to physical stress, ensuring uninterrupted data transmission and reliable results.

Additionally we explored the device's voltage consumption and stability during data transmission via BLE connectivity. Minor resonance observed during data transmission did not affect the device's stability or performance, reaffirming its robustness in real-world scenarios.

Finally, we delved into the analysis of the RTC and oscillator crystal within the WWD. These components are critical for precise timing, data synchronization, and maintaining accurate timekeeping, all of which are essential for effective patient monitoring.

This chapter provides a comprehensive overview of our flexible WWD's capabilities and resilience under various conditions. The device's adaptability to environmental factors, durability under stress, and precise timing capabilities position it as a valuable tool in the field of healthcare technology, particularly in wound monitoring applications.

CONCLUSION

This thesis has explored the design and evaluation of a Flexible Wireless Wearable Device, designed for applications in healthcare, particularly wound monitoring. This research has involved careful design, component selection, rigorous testing, and experimentation to assess the device's functionality and resilience under various simulated conditions.

In this concluding chapter, we summarize the key findings and contributions of this work while reflecting on its significance in the realm of healthcare technology.

5.1 Key Findings and Contributions

Throughout the course of this thesis, several key findings and contributions have emerged:

We meticulously designed the flexible WWD to meet the unique demands of wound monitoring applications. It incorporates a flexible PCB, sensors, and a compact Li-ion battery, allowing for comfortable and non-intrusive placement on the patient's body.

Temperature and humidity are crucial environmental factors in wound care. The experiments conducted in this research have demonstrated the device's ability to maintain accurate data transmission under various temperature and humidity conditions, ensuring optimal wound healing conditions.

The sponge rubber prototype case, designed for the flexible WWD, offers practicality and user-friendliness. Its adaptability to different wound types and body locations enhances patient comfort and convenience.

The device exhibited remarkable durability and resilience during bending, deformation, and exposure to physical stress. It maintained stable power output and data transmission even under these conditions, ensuring uninterrupted monitoring.

The analysis of voltage stability during data transmission via BLE connectivity revealed that the device remains stable and reliable, with minor resonances having negligible effects on its performance.

The RTC and oscillator crystal within the device were shown to be critical for precise timing, data synchronization, and maintaining accurate timekeeping, essential for effective patient monitoring.

5.2 Significance

The research presented in this thesis holds significant implications for the field of healthcare technology, particularly in wound monitoring applications. The flexible WWD offers a promising solution for non-intrusive and real-time wound monitoring, providing accurate data on temperature and humidity conditions critical for optimal wound healing. Its resilience under various environmental and physical stressors positions it as a valuable tool for long-term patient care.

In conclusion, this thesis has contributed to the development of a flexible WWD that has the potential to revolutionize wound monitoring in healthcare. Its adaptability, durability, and precise timing capabilities make it a valuable asset in improving patient outcomes and enhancing the quality of wound care. As technology continues to advance, the flexible WWD represents a promising step towards more effective and patient-centric healthcare solutions.

FUTURE WORKS

As we look ahead to the future of Wireless Wearable Devices, several promising avenues for research and development emerge. Future research directions may include further refinement of the device's design, exploring alternative power sources, and conducting extensive clinical trials to validate its effectiveness in real-world healthcare settings.

Additionally, the integration of advanced data analysis techniques and machine learning algorithms could enhance the device's capabilities for predictive wound care.

6.1 Enhanced Environmental Sensing

Future work may involves advancing the environmental sensing capabilities of WWDs. While our flexible WWD demonstrates resilience to temperature and humidity variations, there is room for improvement in terms of sensing a broader range of environmental parameters. Research could focus on integrating additional sensors, such as air quality sensors or infection risk indicators, to provide a more comprehensive picture of the wound's surroundings. This would empower healthcare providers with even more data for informed decision-making and patient care.

6.2 Advanced Data Analytics

Future research can delve into more advanced data analytics techniques to extract deeper insights from the data collected by WWDs. Machine learning algorithms and predictive modeling could be applied to the sensor data to identify early signs of complications or infection, allowing for proactive intervention. Moreover, the development of user-friendly software applications that can interpret and visualize the data for both healthcare professionals and patients could enhance the practical utility of WWDs.

6.3 Long-Term Wearability and Comfort

Improving the long-term wearability and comfort of WWDs is another area ripe for exploration. Future research could focus on developing even more flexible and lightweight materials for device casings to maximize patient comfort. Additionally, investigating novel attachment methods that minimize skin irritation and ensure secure placement over extended periods could enhance patient compliance with wearing the device.

6.4 Power Efficiency and Battery Life

Efforts to optimize power efficiency and extend battery life are crucial for the practicality of WWDs. Future work could involve the development of energy harvesting mechanisms to supplement or recharge the device's battery. Additionally, exploring low-power hardware components and firmware optimizations can contribute to longer operational lifespans, reducing the frequency of battery replacements.

6.5 Clinical Validation and Regulatory Compliance

Rigorous clinical validation studies are essential to bring WWDs closer to widespread clinical adoption. Future research can focus on conducting large-scale trials to assess the device's performance and reliability in real-world clinical settings. Furthermore, ensuring compliance with healthcare regulatory standards and obtaining necessary certifications will be a critical step toward commercialization.

6.6 Patient-Centered Design

The future of WWDs should prioritize patient-centered design principles. Research can delve into user experience studies and feedback collection to tailor device features and interfaces to the specific needs and preferences of patients. This approach can lead to more user-friendly and intuitive WWDs that patients are more inclined to use consistently.

6.7 Integration with Telemedicine

Given the growing importance of telemedicine, future work could explore seamless integration between WWDs and telehealth platforms. This integration would enable real-time remote monitoring by healthcare providers, facilitating timely interventions and reducing the need for frequent in-person visits.

6.8 Ethical and Privacy Considerations

As WWDs become more prevalent, ethical and privacy considerations will gain prominence. Future research should delve into ethical frameworks and privacy-enhancing technologies to ensure that patient data is securely managed and those individuals' rights and autonomy are respected throughout the monitoring process.

In conclusion, the future of wearable wound monitoring devices holds tremendous potential for improving patient care and healthcare outcomes. By advancing environmental sensing, data analytics, wearability, power efficiency, clinical validation, user-centered design, telemedicine integration, and addressing ethical and privacy concerns, the field can continue to evolve and positively affect the healthcare landscape. As researchers and innovators, we have a vital role to play in realizing this future and bringing these technologies to the forefront of patient care.

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