2024 IEEE 20th International Conference on Body Sensor Networks (BSN) | 979-8-3315-3014-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/BSN63547.2024.10780577

HealthHub: A Wearable Health Prototyping Toolkit

Rishabh Goel
School of Interactive Computing
Georgia Institute of Technology
Atlanta, USA
0000-0001-5828-5019

Josiah Hester
School of Interactive Computing
Georgia Institute of Technology
Atlanta, USA
0000-0002-1680-085X

Alexander T. Adams
School of Interactive Computing
Georgia Institute of Technology
Atlanta, USA
0000-0001-5811-3153

***Abstract*—Wearable health devices have transformed the landscape of vital sign monitoring by enabling continuous, unobtrusive data collection. These compact and lightweight devices bypass the need for large, specialized instruments, facilitating frequent and comprehensive health monitoring essential for diagnosing various medical conditions. Researchers are leveraging innovative techniques to sense bodily functions through external signals, such as using acoustic signals for joint health and repurposing low-cost sensors like IMUs, temperature sensors, and microphones as biosensors. These advancements aim to create more affordable and widespread health monitoring systems than traditional, costly biosensors.**

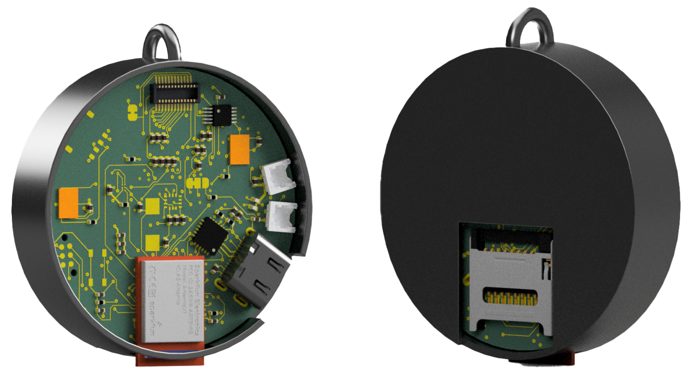
In this work, we present HealthHub, a versatile wearable health prototyping toolkit designed to expedite the development and testing of wearable health devices. HealthHub's modularity and flexibility are demonstrated by its array of onboard sensors and its support for custom snap-on boards that enhance sensing capabilities via the onboard ADC. Our evaluation of HealthHub included testing its power consumption and performance in measuring respiration, where it functioned as a pendant. The system operated for three days on a single coin cell battery, recording data at high sample rates and fidelity.

HealthHub proves to be a lightweight, compact, and highly adaptable platform for developing wearable health devices. Its robust performance and extendable design make it an invaluable tool for researchers and developers in wearable health technology, facilitating the rapid conversion of innovative ideas into functional prototypes.

***Index Terms*—Wearable Health, Sensing, Platform**

I. Introduction

Wearable health devices have revolutionized the monitoring of vital signs in patients and the general population. These devices are designed to be small and lightweight, allowing for easy attachment to the body for continuous monitoring. The compact design eliminates the need for large specialized instruments, enabling more frequent and comprehensive data collection. This continuous data collection is crucial in diagnosing various medical conditions, providing new insights into patient health that were previously unattainable with intermittent monitoring methods. Wearable health monitoring devices have been used to help people with mental health issues [1], reduce hospital stays [2], and monitor vital signs for patients with diabetes [3]. Researchers are exploring innovative techniques to sense bodily functions and assess physiological states using external signals. For instance, the study on knee health employs acoustic signals as bio-signals to gain insights into joint health. Similarly, advances are being made in utilizing existing low-cost sensors commonly found in smart devices, such as inertial measurement units (IMUs), temperature sensors, and microphones, as biosensors. These sensors can be repurposed to develop systems that are more affordable and widespread compared to traditional, expensive biosensors. Microphones have been used to track knee health [4], accelerometers based patches have measured respiration rate and wheezing [5], contact microphones have been used to monitor cardiopulmonary signals [6] and custom boards have been used to create smart face masks to help curb the spread of COVID 19 [7].



(a) Front view (b) Back view

Fig. 1: Full system with enclosure

The development of these wearable health solutions often necessitates the creation of custom hardware that integrates sensors and data acquisition units. Researchers invest considerable time and effort in designing these small, low-power boards, which frequently share components with other wearable health devices. Typically, these boards include high-fidelity analog-to-digital converters (ADCs) to collect data from biometric sensors, such as electroencephalograms (EEG) and electrocardiograms (ECG). These often are connected to an external data acquisition unit to collect data from all the sensors during testing. This often leads to a situation where the test prototype is not a true wearable device since there are still wires connecting the prototype to an external data board and batteries. Common solutions to this problem involve using a prototyping platform in the early stages of development to help aid in the design process. Similar platforms have helped ease the frustrations in fields such as battery-free computing [8], environmental monitoring [9] and more but no good solution exists for wearable health devices yet.

Our solution integrates commonly used sensors and, a data acquisition unit alongside an ultra-low power processor and BLE to create a single wearable prototyping platform suitable for health monitoring. Additionally, it also supports external sensors and electronics through connectors that provide interfaces for 8-channel ADC, SPI, I2C, UART, and I2S. The board can be programmed and access serial communication through the USB C connector. The board can be powered via the USB-C connector, external battery, or external fixed power source.

II. Overview

A. System

This platform enables quicker development and rapid prototyping for smart wearable health sensing applications. The small footprint enables it to be used as a wearable. The PCB has a low-power microcontroller with BLE, sensors like IMU and temperature, and high-precision low-power ADC. The data can be collected on board via an SD card or flash memory or be sent remotely via BLE. The board can be powered via USB-C or an external LiPo battery. The wearable health board is a modular plug-and-play hardware design that has an inbuilt sensor as well as support for peripheral modules. The board is designed around the Apollo 3B processor from Ambiq Electronics because it is one of the lowest power processors on the market with BLE. We opted to use the Artemis module designed by SparkFun which integrates a BLE antenna as well as an RF shield to the processor. Our boards comprise a variety of sensors that can be used for sensing biosignals. The main feature is the 8 simultaneous channel 16-bit ADC that can be used to collect data from external biosensors. The ADC is capable of accepting single-ended and differential signal sampling at up to 8000 samples per second. The ADC inputs are accessible via the 20-circuit slim-stack dense connector which attaches peripheral boards with the sensors and front-end circuitry. To save power we have also included a multiplexer on the first 2 ADC channels which can route the signal to either the lower power on board ADCs built into the processor or the high fidelity and higher power external ADC.

The onboard sensor suite includes a 6-axis inertial measurement unit IMU, ASM330LHB, 2 temperature sensors (TMP117) placed on both sides of the board which could provide skin temperature as well as ambient temperature, 2 microphones that can be used as mono or stereo microphones. To collect data we have designed the board with a micro SD card slot to dump data being collected. This can then be transferred to a computer at a later time for processing. Additionally, the board also has 2MB of FRAM which provides lower-power nonvolatile memory for lower-power applications. Data stored can also be transferred wirelessly in real-time or bulk from nonvolatile memory using the built-in BLE 5 module.

The board has been designed with power efficiency in mind to enable its application in the wearable sensing domain

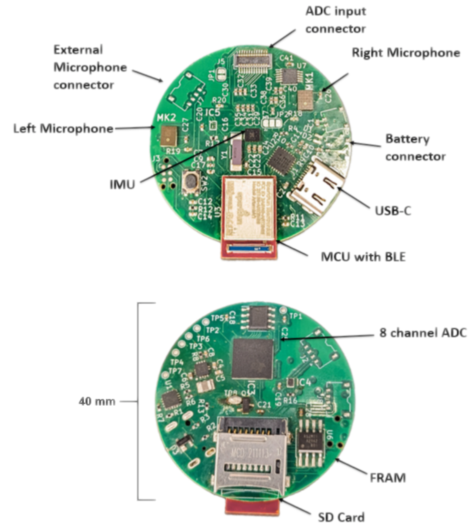


Fig. 2: Health Hub PCB Overview

Component	Part	Power (mW)
ADC	ADS1198CZXGT	0.55/channel
IMU	ASM330LHHTR	2
Temperature	TMP117AIYBGR	0.01
Microphone	SPK0838HT4H-1	1.9
SD Card	693072010801	150
FRAM	MB85RS2MT	30
Microcontroller	Artemis	1

without relying on heavy batteries. Parts were chosen to reduce power consumption while maintaining high fidelity. We were able to have an operating power of 25mW without utilizing sleep mode which would enable this board to run off a 2450 coin cell battery for 3 days of continuous testing and data collection

B. Application

Previous works have looked at capturing sounds made by the body to gain key insights about the user's health and vital signs. Surface microphones were used in body beat[10] to detect nonspeech body sounds and wearable breath sensors have been used to monitor breathing patterns. These works and similar endeavors often require the same basic components of a microcontroller, data acquisition system, and power circuitry with only minor changes to the sensing system used, i.e., in this case, the microphones. We chose to recreate such an acoustic health wearable device to measure respiration sounds using the Health hub. The onboard microphones of the HealthHub, being port microphones, are not suitable for this task as they tend to pick up a significant amount of background noise. To overcome this limitation and enhance our signal detection, we integrated a Knowles BU-21771 microphone into our system.

The BU Series piezo-ceramic accelerometer, which includes the BU-21771, operates within an output range from 20 Hz to above 10 kHz. This type of microphone is primarily used as a contact microphone in high-noise environments and can also

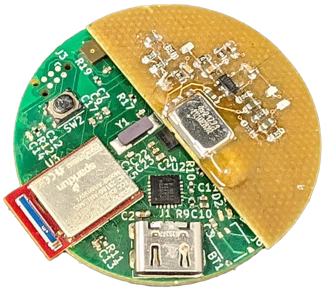


Fig. 3: Health Hub with a microphone module attached

function as an accelerometer for lightweight structures. It is versatile in its application, being wearable on the throat or a bony part of the head, such as the top, temple, or mastoid bone. Furthermore, it is commonly integrated into helmet designs for radio communication in military and emergency services. The use of the BU-21771 microphone in our prototype helps eliminate background noise, providing a better signal-to-noise ratio for respiratory sounds.

To facilitate the integration of the BU-21771 microphone with the HealthHub, we designed a specialized microphone board. This board can easily snap onto the ADC connector of the HealthHub. The signal from the microphone is biased to 1.5 V before being amplified through a single-stage amplifier with a gain of 30. This setup ensures that the respiratory sounds are captured with higher clarity and precision, significantly improving the accuracy of wheezing detection in various environments.

III. Experiments

We tested the microphones to ensure they would perform sufficiently to capture data about wheezing and only pick up signals on the surface of the skin. This should lead to better external noise rejection for a better signal. All testing was conducted with the microphone and speaker separated by a layer of humic gel. Humimic Medical is a leading producer of high-grade medical products, best known for their durable, quality, and reusable ballistic gel. These synthetic gelatins are used globally by medical professionals for simulations, phantom imaging, and realistic training. This allows us to create a close representation of recording respiration sounds through a microphone placed on the chest. The following experiments were conducted to verify the performance of our microphone board.

Microphone frequency response test: We adhered our test microphone, HealthHub with the microphone board and a speaker to the same solid worktop. we then played a sinusoidal sweep from 30Hz-4kHz.

Frequency Response through Humimic: For this test we played a sine sweep from 30Hz to 4kHz and recorded the response of the microphone through humimic. For this test, we repeated the experiment and recorded data with both a normal USB microphone as well as our accelerometer-based microphone.

SnR test through humimic with background noise: For this test we played the sine sweep again but also had background noise to simulate a real-world scenario. The background noise we tested included testing in an environment with people talking, background music as well as playing static white noise in the background.

IV. Results

Figure 4 summarizes the results of the experiments conducted to validate HealthHub's performance for the application of recording respiratory sounds. The frequency response spectrum of both the HealthHub Knowles microphone and the test microphone is shown. The HealthHub has a flatter response in the testing range of 30Hz-4kHz. A flat frequency response in a microphone for respiratory recording ensures accurate capture of all sound frequencies, providing a true representation of the respiratory sounds. This accuracy is crucial for reliable analysis and diagnosis, as it prevents distortion and ensures consistent sensitivity across the frequency spectrum. Additionally, it simplifies calibration and enhances the microphone's versatility for different respiratory sounds.

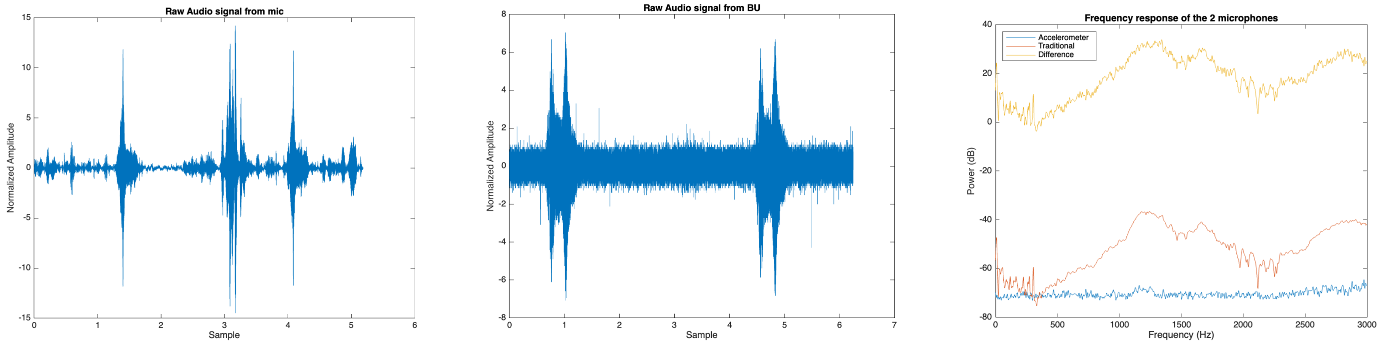
The final tests with background noise show the advantage of using these microphones with a custom board since they can reject a majority of the background noise in the environment. The Knowles microphone had an SnR of 11.9 dB vs -1 dB for the traditional microphone.

V. Conclusion

In this work, we present HealthHub , a versatile wearable health prototyping toolkit designed to streamline the development and testing of wearable health devices. By enabling researchers to rapidly transform ideas into functional prototypes, HealthHub significantly reduces the friction associated with traditional prototyping methods. We have shown the modularity and flexibility of this board by presenting the wide variety of onboard sensors we have provided on the board as well as its support to create custom snap-on boards to add more sensing capabilities to the board by utilizing the onboard ADC.

Our evaluation of HealthHub focused on its power consumption and performance in the application of measuring respiration, utilizing the board as a pendant. The results demonstrated that the system can operate for three days on a single coin cell battery while maintaining a high sample rate and data fidelity. This capability underscores the practicality and efficiency of HealthHub for long-term monitoring applications.

Overall, HealthHub proves to be a lightweight, compact, and highly adaptable platform for developing wearable health devices. Its robust performance and extendable design make it a valuable tool for researchers and developers in the field of wearable health technology.



(a) Raw test microphone data

(b) Raw accelerometer microphone data

(c) Frequency response diff

Fig. 4: Data from audio experiments

References

[1] Jussi Seppälä et al. "Mobile Phone and Wearable Sensor-Based mHealth Approaches for Psychiatric Disorders and Symptoms: Systematic Review". In: *JMIR Mental Health* 6.2 (Feb. 20, 2019), e9819. DOI: 10.2196/mental.9819. URL: https://mental.jmir.org/2019/2/e9819.

[2] Th. Katsaras et al. "The use of the "Healthwear" wearable system in chronic patients' early hospital discharge: Control randomized clinical trial". In: *2011 5th International Symposium on Medical Information and Communication Technology*. 2011 5th International Symposium on Medical Information and Communication Technology. ISSN: 2326-8301. Mar. 2011, pp. 143–146. DOI: 10.1109/ISMICT.2011.5759815.

[3] Richard R. Fletcher, Ming-Zher Poh, and Hoda Eydgahi. "Wearable sensors: Opportunities and challenges for low-cost health care". In: *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology*. 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology. ISSN: 1558-4615. Aug. 2010, pp. 1763–1766. DOI: 10.1109/IEMBS.2010.5626734. URL: https://ieeexplore.ieee.org/abstract/document/5626734.

[4] Mohammad Nikbakht et al. "KneeMS: A Low-Cost Wireless Wearable System to Monitor Knee Acoustic Emissions". In: *2023 IEEE 19th International Conference on Body Sensor Networks (BSN)*. 2023 IEEE 19th International Conference on Body Sensor Networks (BSN). ISSN: 2376-8894. Oct. 2023, pp. 1–4. DOI: 10.1109/BSN58485.2023.10330997. URL: https://ieeexplore.ieee.org/document/10330997.

[5] Brian Sang et al. "An Accelerometer-Based Wearable Patch for Robust Respiratory Rate and Wheeze Detection Using Deep Learning". In: *Biosensors* 14.3 (Mar. 2024). Number: 3 Publisher: Multidisciplinary Digital Publishing Institute, p. 118. ISSN: 2079-6374. DOI: 10.3390/bios14030118. URL: https://www.mdpi.com/2079-6374/14/3/118.

[6] Pranav Gupta et al. "Precision wearable accelerometer contact microphones for longitudinal monitoring of mechano-acoustic cardiopulmonary signals". In: *npj Digital Medicine* 3.1 (Feb. 12, 2020). Publisher: Nature Publishing Group, pp. 1–8. ISSN: 2398-6352. DOI: 10.1038/s41746-020-0225-7. URL: https://www.nature.com/articles/s41746-020-0225-7.

[7] Alexander Curtiss et al. "FaceBit: Smart Face Masks Platform". In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5.4 (Dec. 27, 2021), pp. 1–44. ISSN: 2474-9567. DOI: 10.1145/3494991. URL: https://dl.acm.org/doi/10.1145/3494991.

[8] Abu Bakar et al. "Protean: An Energy-Efficient and Heterogeneous Platform for Adaptive and Hardware-Accelerated Battery-Free Computing". In: *Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems*. SenSys '22: The 20th ACM Conference on Embedded Networked Sensor Systems. Boston Massachusetts: ACM, Nov. 6, 2022, pp. 207–221. ISBN: 978-1-4503-9886-2. DOI: 10.1145/3560905.3568561. URL: https://dl.acm.org/doi/10.1145/3560905.3568561.

[9] Elise Saoutieff et al. "A Wearable Low-Power Sensing Platform for Environmental and Health Monitoring: The Convergence Project". In: *Sensors* 21.5 (Jan. 2021). Number: 5 Publisher: Multidisciplinary Digital Publishing Institute, p. 1802. ISSN: 1424-8220. DOI: 10.3390/s21051802. URL: https://www.mdpi.com/1424-8220/21/5/1802.

[10] Tauhidur Rahman et al. "BodyBeat: a mobile system for sensing non-speech body sounds". In: *Proceedings of the 12th annual international conference on Mobile systems, applications, and services*. MobiSys'14: The 12th Annual International Conference on Mobile Systems, Applications, and Services. Bretton Woods New Hampshire USA: ACM, June 2, 2014, pp. 2–13. ISBN: 978-1-4503-2793-0. DOI: 10.1145/2594368.2594386. URL: https://dl.acm.org/doi/10.1145/2594368.2594386.