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ModAu: Modernized Auscultation

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***Abstract*—This paper presents a novel wireless digital stethoscope design that integrates multiple sensing modalities into a compact form factor. The proposed stethoscope aims to enhance the auscultation data quality by capturing high-quality audio and precise vibration data for improved diagnosis and monitoring of respiratory and cardiac conditions. To enable wireless connectivity, the auscultation device incorporates the latest Bluetooth technology, enabling real-time transmission of auscultation data to a compatible device, such as a smartphone or computer. This allows future healthcare professionals to visualize and analyze the captured data using dedicated software, providing enhanced visualization tools, signal processing algorithms, and machine learning techniques for accurate interpretation and diagnosis. The compact form factor and low-cost design of the stethoscope, makes it suitable for various medical applications, including remote healthcare and long term monitoring.**

***Index Terms*—Sensor arrays, Accelerometers, Digital Auscultation**

I. Introduction

Stethoscopes have long been a symbol of the medical profession, serving as the primary tool for auscultation, or the act of listening to internal sounds of the body. Since its invention [1], the classic acoustic stethoscope has been a reliable companion to physicians, allowing them to detect and diagnose various conditions. However, with the advancements in technology, a new era of stethoscopes has emerged: the digital stethoscope has become a valuable tool in diagnosing and monitoring respiratory and cardiac health. This technology combines the traditional idea of a stethoscope with digital sensors and advanced signal processing algorithms to enhance the detection and analysis of auscultatory sounds.

The use of digital stethoscopes has many advantages. First, electronic stethoscopes are not dependent on (intra-person-varying) human hearing, as microphones can be used that are more sensitive than the human ear. Second, electronic stethoscopes are able to digitally store their auscultation recordings which allows for the computerized analysis of auscultation recordings. Heart sound anomalies and lung sound artifacts can be detected using various machine learning algorithms in an objective manner [2]–[6]. Studies have shown physicians are often not in consensus on their subjective auscultatory findings [7]. Moreover, multiple systems have been proposed that automatically (partially) diagnose patients based on their respiratory recordings [3]. Additionally, visual representations of the recordings, such as spectrograms, can be made to aid the interpretation process of the medical expert.

Next to computer-aided analysis of recordings, digital stethoscopes also offer great potential for remote patient monitoring applications [8], [9]. With the advent of telemedicine solutions, healthcare providers can now listen to patients' lung sounds in real time, even if they are located in different geographical areas. By transmitting the recorded sounds through secure digital platforms, physicians can evaluate respiratory status, provide remote consultations, and offer timely interventions. This capability is particularly valuable for patients who have limited access to specialized respiratory care or live in remote regions.

In the remainder of this paper the hardware architecture of the developed auscultation unit, also referred to as the Modernized Auscultation (ModAu) sensor, will be presented in combination with an overview of its capabilities. In the subsequent section the experimental setup and its results are described. In the final section, we will discuss our proposed system, the experimental results and the envisioned road map for this auscultation unit as future work.

II. Hardware architecture

While the traditional stethoscope uses a combination of a cup-shaped bell with a diaphragm to capture body sounds and air-filled hollow tubes to transmit the sounds to the physicians' ears, the digital counterpart needs to be able to capture the sound pressure waves emitted by a patient's body and digitize these. This implies combining sensing modalities capable of capturing sound pressure waves with an embedded device that can interpret and relay this information to a computer (being either a PC, tablet or other mobile device).

Given the envisioned application of using this compound sensing device as an auscultation unit, the proof-of-concept sensor system could not be constructed as a combination of off-the-shelve IC (Integrated Circuits) development kits since such a system would be too bulky or clumsy to provide

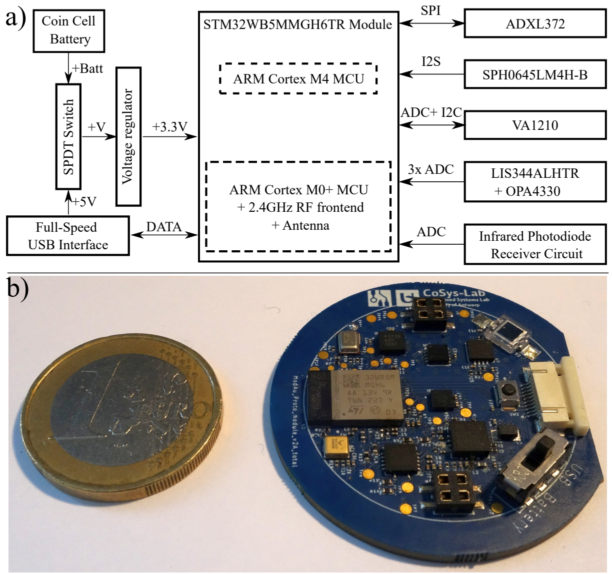

Fig. 1. a) System architecture of the ModAu auscultation device with the STM32WB5MMGH6TR at its core. b) The assembled sensor measuring 40mm in diameter.

sensible data and also affect the body sounds due to its relatively large size and weight. Therefore, the envisioned auscultation unit needs to be a compromise of minimizing form-factor and weight while maximizing functionality to provide us with a varied set of sensible data. To reflect the traditional stethoscope, the size of the ModAu sensor was restricted to 40mm where all the electronics fit within a diameter of 32mm, giving a small edge for adhering the device with medical tape to a subject.

A. Hardware Components

The core of this sensing device consists of the STMicroelectronics STM32WB5MMGH6TR module, as can be seen in the hardware architecture in figure 1. This module combines the STM32WB55VGY wireless dual-core Cortex-M4 and Cortex-M0+ microcontroller with indispensable system components, e.g. frequency and switched-mode power supply circuits together with an integrated antenna, antenna matching and internal passive devices for harmonics rejection and RF matching. While some GPIO becomes unavailable, the System on Module enables miniaturizing the overall PCB (Printed Circuit Board) in combination with a simplified and verified RF (Radio Frequency) design. The module also offers a Full-speed USB interface that can be used for either programming the module or as a data interface for communication with a computer.

While the USB connection can provide power, the module also has an add-on board that features a coin cell retainer compatible with 2016 lithium coin cells in order to power the sensing device for untethered operation. Given that these cells have up to 90mA h of capacity and the sensing module uses approximately 45mA, without any power optimizations, it offers about 2 hours of operation time. To improve the autonomy, the firmware can be optimized with (deep) sleep modes or by choosing a different battery type. The latter, however, is also a trade-off between battery capacity and its weight that will influence the measurements.

In order to assess a patients condition and capture their bodily sounds, a multitude of sensing modalities has been incorporated into the ModAu device. Two three-axis MEMS accelerometers have been integrated on the PCB, the STMicroelectronics LIS344ALHTR and the Analog Devices ADXL372. These devices were deemed interesting due to their wide bandwidth characteristics and presumed adequate sensitivity for picking up the body's vibrations. Accompanying these sensors, a third accelerometer was added to the system design, being the Vesper VA1210 Piezoelectric MEMS voice accelerometer which is marketed as a type of bone conduction microphone. As a fourth sensor modality a more traditional bottom port digital MEMS microphone from Knowles, a SPH0645LM4H-B, was also integrated into this sensor. When we add up the PCB and component costs for this sensing device, the unit price of the auscultation unit adds up to €143 which can be further reduced when ordered in larger production quantities.

B. Supported Wireless Protocols

The proposed wireless digital auscultation device with its built in RF-coprocessor is designed to support multiple wireless protocols that operate on the 2.4GHz ISM band for seamless connectivity. It incorporates Bluetooth LE 5.3, 802.15.4, Zigbee, Thread, and Matter protocols, ensuring compatibility with various platforms. Bluetooth LE 5.3 enables efficient transmission of auscultatory data to smartphones, tablets, or computers. Its compatibility with 802.15.4, Zigbee, Thread, and Matter protocols facilitates integration with wearables and healthcare systems while ensuring secure data transmission and complying with healthcare regulations. The device's versatility allows for easy integration with different devices and systems, enhancing collaborative healthcare practices.

C. Multi-lead Auscultation

While digital auscultation can already provide improved medical diagnosis, multi-lead auscultation provides a more comprehensive assessment of respiratory and cardiac sounds compared to single-lead methods. By using multiple sensors or stethoscope placements, it captures information from different anatomical locations simultaneously, allowing for better detection of abnormalities and localized variations. This approach enhances diagnosis accuracy, especially in cardiovascular conditions. Additionally, multi-lead auscultation facilitates noise reduction, improves signal quality, and enables the study of sound propagation. Synchronization of data from multiple leads aids in comparing timing and intensity, leading to a more precise understanding of auscultatory findings. Our proposed ModAu sensor is inherently designed to support multi-lead auscultation by using the latest Bluetooth 5 standard, which supports up to seven devices simultaneously on one host, and features a built-in synchronization methodology. For the latter, an infrared photodiode receiver circuit [10] was integrated and is connected to one of the module's ADC enabled GPIO pins. By generating infrared light pulses with random on-off times using an infrared LED array, a random 1-bit signal will be embedded into the sensor data stream. Multiple ModAu sensors can be synchronized in post-processing by calculating and adjusting for the time-shift between the 1-bit random data streams from every device which can be found by using the cross correlation, as demonstrated in our previous work [11].

III. Experimental Results

For evaluating the proposed digital auscultation sensor with its multiple sensor modalities, an experimental setup was created using a Focal Alpha 50 studio monitor that emits linear frequency sweeps between 20Hz and 2kHz. This allows us to measure the frequency response of the different sensors present on the ModAu prototype. To create a surface that mimics the human chest, an intermediate layer of ballistic gel was laid on top of the loudspeaker with a Bruel & Kjaer Type 8104 hydrophone incorporated into the gel to provide reference acoustic data. We also recorded the response of the ThinkLabs One stethoscope as a reference for a commercially available digital stethoscope. A sketch of the setup is shown in figure 2. To generate the 30s frequency sweep and to record the hydrophone signal, a National Instrument USB-6356 (BNC) data acquisition device was utilized with a sample frequency of 44.1kHz.

To calculate the power spectra of the signals recorded by the ModAu prototype, the ThinkLabs One stethoscope and the hydrophone, first, the DC-component of all signals was removed. Next, the signals were resampled (if needed) to 44.1kHz. Finally, we calculated the power spectrum utilizing Welch's method [12] using a Hann window with a length of 22050 samples and an overlap of 90%. To measure the actual frequency response of the sensors present on the ModAu and the ThinkLabs One stethoscope, we divided the frequency spectra of the sensor signals by the frequency spectrum of the hydrophone signal. This was done to counteract the frequency characteristics of the loudspeaker and ballistic gel. The frequency responses were also normalized w.r.t. their respective noise floors. The noise floor for each sensor was defined as the average signal power within the frequency range 20Hz to 2kHz when the speaker was powered off. The results can be seen in figure 3. The results of the the ADXL372 accelerometer were not included since the SNR was too low and was thus found not to be sensitive enough for the intended application.

IV. Discussion and Conclusion

In this paper we propose the ModAu sensor as a compact, low-cost digital wireless auscultation device that incorporates multiple sensors to capture bodily sounds. Given the nature of the application this device can also be seen as an experimental platform for evaluating the chosen sensor modalities. When we assess the frequency response curves of the raw sensor data, we can see that the Knowles microphone resembles the characteristics of the Thinklabs One digital stethoscope for low frequencies, and even outperforms it in the frequency range 600Hz to 2kHz. This is a desirable characteristic for the recording of respiratory crackles which are present within the frequency range 100Hz to 2kHz [13]. While the ADXL372 accelerometer and the VA1210 voice accelerometer appeared to be least suitable for auscultation purposes, the LIS344ALHTR accelerometer does show some promise due to its sensitivity and bandwidth. We therefore believe that a combination of the Knowles microphone and the Z-axis of the LIS344ALHTR could be key to achieve more qualitative auscultation recordings while using the X and Y-axis of the accelerometer to detect and help suppress motion artifacts.

As future work, we want to use deep learning denoising neural networks [14]–[16] that make use of the aforementioned best-candidate sensing modalities to further improve the auscultation data. Another method for improving the quality of the auscultation data would be transitioning the PCB design from a rigid FR4 material to a flexible PCB that fits to a patient's body curvature. In order to further improve the battery autonomy, the data acquisition could make use of a technique called compressed sensing [17]–[20] which would allow sampling the sensor data at a rate below the Nyquist rate, thus reducing power consumption due to lower clock-speeds but also requiring lower (wireless) data transmission rates.

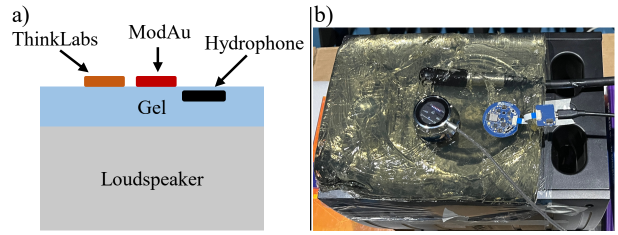

Fig. 2. Schematic representation and photograph of our experimental setup to measure the sensors' frequency responses shown in respectively a) and b).

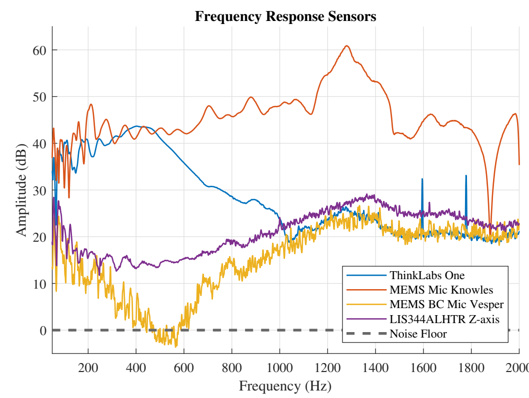

Fig. 3. The measured frequency responses of the ThinkLabs One stethoscope, both MEMS microphones and the Z-axis of the accelerometer LIS344ALHTR. (the Z-axis is pointed perpendicular to device's contact surface)

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