Sensor Systems

Pulse Wave Measurement With In-Ear Headphones While Music Playback

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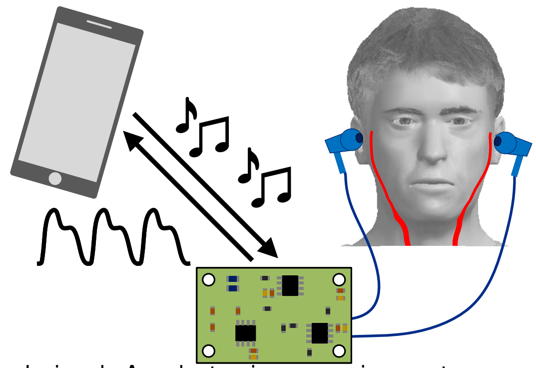

Abstract—The continuous acquisition of the arterial pulse wave can be used to determine the heart rate and to estimate the blood pressure. Existing wearables require special sensors and often only detect the pulse wave at the extremities from the peripheral blood vessels, far away from the heart and aorta. In addition, these wearables are sometimes expensive and uncomfortable. The objective of this work is therefore the development of a comfortable wearable measurement system that continuously acquires the pulse wave. The approach presented in this work is based on the minor deformation of the ear canal when the pulse wave arrives. By sealing the ear canal using commercial headphones, these deformations are converted into small changes in air pressure. These pressure changes are detected directly by the headphones and converted into an electrical signal. An electronic measuring system was developed to record pulse waves and play music simultaneously. This system can be connected between any conventional audio source and headphones. The measuring system digitizes the low-frequency signal components and transmits them to an analysis system such as a smartphone or PC. On this system, the signals undergo a digital signal processing chain. A subject measurement was conducted to evaluate the measurement approach. The music being played and an electrocardiogram were also recorded used as reference signals. The measurement demonstrated that with the new system, the pulse waves in both ears can be recorded during music playback with simple headphones and correlate with the electrocardiogram.

Index Terms—arterial stiffness, electrocardiography, in-ear headphones, pulse wave, wearable.

I. INTRODUCTION

The acquisition and analysis of the arterial pulse wave is of interest for both clinical and fitness applications [1], [2]. Since the pressure wave propagates from the heart through the entire arterial vascular system, it contains important information about the cardiovascular health status. The pulse wave in the large arteries close to the heart is particularly interesting, as their elasticity dampens the pressure pulses [3]. In the past, relationships between the pulse wave and arterial vascular stiffness have been researched. In addition, correlations have been found between pulse wave propagation and blood pressure [4].

Of particular interest are continuous measurements of the pulse wave to observe temporal changes in the vascular system. These can allow conclusions to be drawn about stress situations or perhaps even indicate an upcoming cardiovascular event [5], [6]. In order to record the pulse wave in everyday life, wearables are needed that neither disturb nor impair the users.

In the past, several works of such wearables have already been presented. Many of them focus on smartwatches, glasses, rings or patches [7]–[9]. For detection, the optical method of photoplethysmography (PPG) is often used. However, reproducible positioning can be difficult. In addition, PPG typically only detects the averaged blood pulsations in the peripheral blood vessels [10].

Another method that has been investigated is based on the detection of the pulse wave at the ears. It is assumed that arteries close to the auditory canal, such as the superficial temporal artery or posterior auricular artery, lead to deformation of the auditory canal. In the past, these were detected using a piezoelectric sensor [11]. In another approach, the auditory canal was sealed using orthoplastics or headphones so that measurable pressure changes occur in the auditory canal [12], [13]. These can be recorded using pressure sensors and correspond to the pulse waveform. Their reciprocal behavior enables them to both convert pressure changes into electrical signals and electrical signals into sound.

For a high level of user acceptance, simultaneous music playback and pulse wave measurement would be particularly interesting. There is an initial study that demonstrates the feasibility of this idea [14]. However, a general approach that considers the fact that both the audio source and the headphones are voltage sources in this mode of operation has not yet been published. It must be considered that both sources work in an electrical parallel circuit and the measurement results depend significantly on the inner impedances. In this paper, a compact measurement setup is presented that takes this into account.

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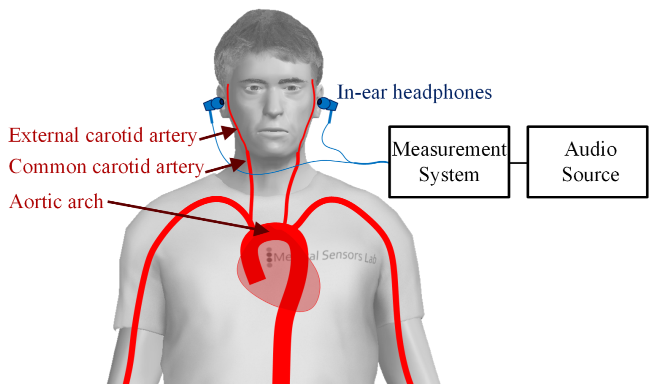

Fig. 1. Measurement approach to acquire the arterial pulse wave with commercial in-ear headphones.

Its implementation can easily be used between any audio source and commercial in-ear headphones that provide a tight seal around the ear canal. The functionality is tested by means of a subject measurement using an electrocardiogram (ECG) as reference.

II. MEASUREMENT APPROACH

An overview of the measurement approach is shown in Figure 1. With each heartbeat, a volume of blood is pumped into the aortic arch, which propagates in the form of an arterial pulse wave. One part of this volume flows along the Common carotid arteries and the External carotid arteries to the head. These blood vessels are located close to the left and right ear canal. It is therefore assumed that these arteries are mainly responsible for the minor deformations of the ear canal. To measure the pulse wave during music playback in both ears, a pair of commercial in-ear headphones is placed in such a way that they seal the ear canal. The headphones are not connected directly to the audio source, but the signals are processed by a newly developed measurement system. On the one hand, this measuring system allows the audio frequency components that are above the frequency components of typical pulse waves to pass through. On the other hand, it processes the low voltages that occur when the minor pressure changes in the ear move the headphone membranes.

The simplified electrical measurement problem for one of the two audio channels is shown in Figure 2. The audio source is represented by the voltage source V_{AS}. While this is simplified and assumed to be an ideal source, it is also conceivable that it has an output resistance. The headphones are represented by a resistor and a voltage source. The input resistance of the headphones R_{HP} is usually several tens to hundreds of ohms and represents the electrical load for music playback. It has a frequency dependency, which is neglected for simplification purposes. The V_{PW} source represents the low voltages generated by the minimal membrane movements caused by the incoming pulse waves. Assuming this equivalent circuit diagram, the measurement of the source voltage V_{AS} does not enable the extraction of information regarding V_{PW}. Therefore, our approach uses the additional shunt resistor R_{S}, which combines the signal components of V_{AS} and V_{PW} to V_{RS}, according to Equation 1.

$$V_{\mathrm{RS}} = R_{\mathrm{S}} \cdot \frac{V_{\mathrm{AS}} - V_{\mathrm{PW}}}{R_{\mathrm{S}} + R_{\mathrm{HP}}} \tag{1}$$

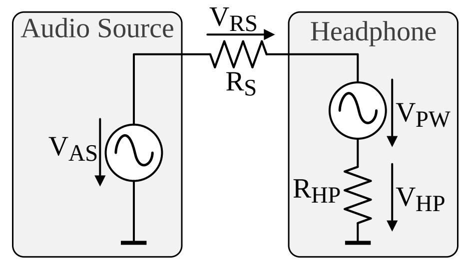

Fig. 2. Simplified equivalent circuit of the electrical measuring problem.

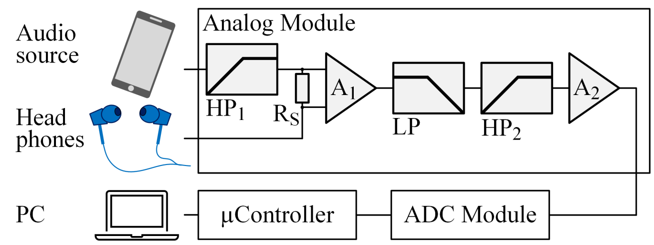

Fig. 3. Block diagram of the developed measurement system to separate the music signals and the pulse wave signals from each other.

III. MEASUREMENT SYSTEM

The goal of the developed measurement system is that both the audio signal is transmitted to the headphones and the pulse wave signal from the headphones is analyzed. The resulting pulse wave signals can be displayed directly on the audio source, such as a smartphone, or alternatively on a connected PC. Figure 3 shows the block diagram of the developed measurement system, which is composed of an analog module, an ADC (analog-to-digital converter) module and a microcontroller system (μController).

To ensure that no unexpected low-frequency signal components from the audio source are processed, the signals first pass through a first-order analog passive high-pass filter (HP_1, f_c = 145 Hz). Subsequently, the audio signals pass through the shunt resistor R_s and the headphones. As shown in Figure 2, the signals generated by the pulse waves also pass through R_s, so that V_{RS} occurs across the shunt resistor. This differential voltage is amplified with an INA (A_1, Instrumentation Amplifier, INA128, Texas Instruments) by a factor of G = 60. In order to remove the audio signal components and high frequency noise from the signal, an active fourth-order low-pass filter (LP, Butterworth, Sallen-Key topology, f_c = 3 Hz), realized with OPAMPS (Operational Amplifiers, OPA2134, Texas Instruments), is used. Since the offset voltages resulting from the analog signal processing steps cannot be neglected in comparison with the expected low pulse wave signal, the signals are again removed from the DC component using a passive first-order high-pass filter (HP_2, f_c = 3 Hz). Finally, the useful signal is amplified by a factor of G = 100 using two operational amplifier stages (A_2, Operational Amplifiers, OPA2134, Texas Instruments).

The output signal of the analog module is digitized by the ADC module. For this purpose, a $\Delta\Sigma$-converter with a resolution of n = 24 bits) and a sampling rate of f_s = 3855 Hz) is used. The data is sent to a microcontroller module (Teensy 4.1, PJRC) via the SPI (Serial Peripheral Interface) interface. This module is used as an interface to the PC or another digital signal processing unit. It handles the

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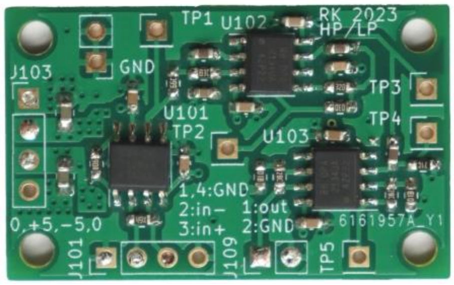

Fig. 4. Assembled circuit board of the analog module. The system has dimensions of $37 \times 23\,\mathrm{mm}^2$.

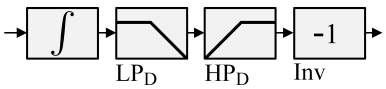

Fig. 5. Digital signal processing chain to reconstruct the pulse waves.

ADC configuration and the transmission of measurement data via the Ethernet interface. The analog module was implemented as a printed circuit board and is shown in Figure 4.

The signal is further processed on the PC as shown in Figure 5. A MATLAB script was developed for this purpose, which implements four steps. Since the headphones work according to the principle of electromagnetic induction, the voltage V_{PW} contains information regarding the temporal membrane movements. To determine the membrane position and thus the pressure in the ear canal, a mathematical integration is first necessary. As the membrane of a headphone is not sealing, but is always compensating pressure, a physical high-pass characteristic occurs. To compensate this, the signal is filtered with a low-pass filter (IIR, Butterworth, N=2, f_c = 8 Hz). To remove the DC component and drift effects, an FIR high-pass filter is also applied. Previous work has shown that not an increase but a decrease in pressure in the ear canal is to be expected when the pulse wave arrives [15]. Although the origin of this inverted coupling has not yet been scientifically clarified, it is removed in this signal processing chain by an inversion.

IV. SUBJECT MEASUREMENTS

A subject measurement was performed to test the functionality of the new measurement approach. This study was approved by the ethics committee of HAW Hamburg (#2024-23). For the measurement, a healthy male adult subject first sat down on a chair and placed the commercial low-cost in-ear headphones (MDR-EX15LP, Sony) in the ear as if the person wanted to listen to music. It was ensured that the headphones were not too loose, but that they sealed the ear canal with their silicone tip. The headphones were then connected to the analog module using the audio jack connection. The audio source, which was the headphone output of a notebook (ThinkPad X1 Yoga G7, Lenovo), was also connected to the analog module. In addition, the notebook was connected to the microcontroller system via the Ethernet interface for signal acquisition. This interface was galvanically isolated by a network isolator (MI 1005, Baaske Medical) to ensure electrical medical safety in accordance with the IEC 60601-1 standard. In order to test the measurement system, two additional signals were recorded as references. The output signal of the audio source was recorded by a storage oscilloscope (WaveSurfer 4104HD, Teledyne LeCroy) with a sampling rate of f_s = 62.5 kHz and a resolution of n = 12 bits so that the pulse wave measurement results can be compared with the simultaneously recorded music. In addition, an ECG was acquired simultaneously with the pulse wave measurement using the ADC module to ensure that the measured pulsations were actually generated by the heartbeat. The subject sat calmly on the chair during the entire measurement. The music played was Piano Concerto in G major No. 17, Allegro, by W. A. Mozart. The music was played at medium volume. To improve the signal separation, low frequencies below 100 Hz were attenuated by 120 dB using software (Equalizer APO 1.3.2). The measured raw signals are shown in Figure 6 for a duration of 100 s. They have been normalized and provided with offsets for better visualization.

The upper plot represents the raw audio signal of a single channel, which was recorded from the audio source using the oscilloscope. The different phases of the composition can be clearly recognized. Below, the black plot shows the recorded ECG. The respective R-peaks are clearly visible in this plot. The blue and red plots are the signals from the new measurement system digitized by the ADC module. On closer examination, periodic peaks can be found which have the same spacing as the ECG R-peaks. However, the shape of the respective pulse wave peaks varies over time and also between the two headphone channels. It is assumed that this is caused on the one hand by the different physiological conditions. On the other hand, insufficient sealing of the auditory canal also influences the signal characteristics [14]. During the measurements, it was also observed that movements of the lower jaw in particular have a significant effect on the signal characteristics. Other movements of the head and the rest of the body also strongly influence the measured signals. These disturbances can generate significantly higher signal amplitudes than the arterial pulse waves. These related movements were minimized in the presented measurement. For future applications, however, algorithms must be developed to detect and remove these artifacts.

Figure 7 shows the digitally processed signals. For better visualization, only a short 6-second time range was plotted. This is located in a particularly loud section of the music. The two resulting processed signals from the ears can be seen below the ECG signal. It can be observed that both signals have waves with slightly different shapes. The EarL channel clearly shows the shape of a typical arterial pulse wave. These appear synchronous with the heart activity that can be recognized from the ECG. In comparison with the literature, the pulse waves appear to have a long delay with respect to the ECG signal [16]. This is mainly caused by the analog signal processing. A circuit simulation has shown that the group delay in the frequency range of the pulse wave is around 230 ms. In the EarR channel, the arterial pulse waveforms are not so clearly recognizable. In comparison with the EarL channel, however, the simultaneous minima and maxima can be identified, so that it can be assumed that the pulsations are also caused by the arterial pulse wave. As described above, the physical transmission path from the artery to the headphone membrane is sensitive to mechanical influences. In addition, the physical properties of the headphone membrane are not known. The compensations made using digital signal processing are therefore not exact and influence the resulting pulse waveforms. Continuous detection of the pulse wave in both ears is therefore challenging under real conditions, but possible. In particular, a subsequent fusion of both pulse wave signals could increase the robustness of the measurement method.

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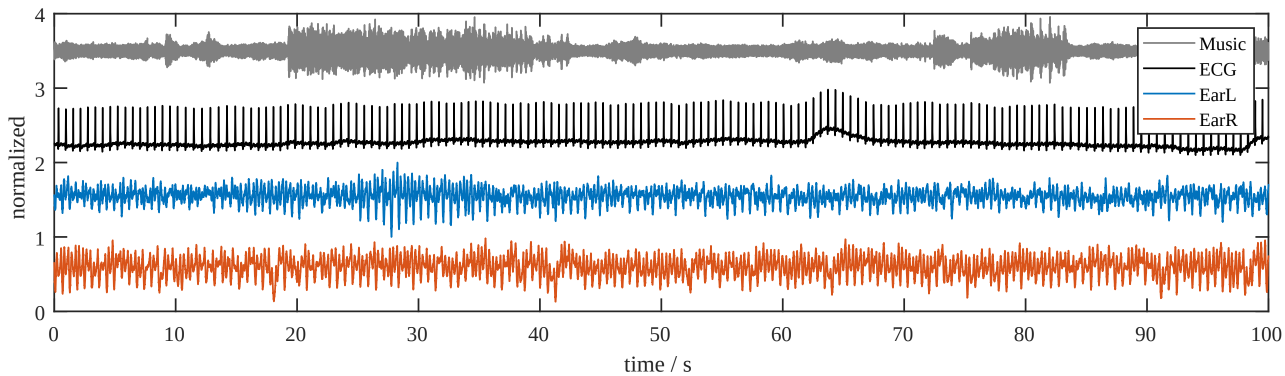

Fig. 6. Acquired raw data for a duration of 100 s. The two upper plots are for reference and allow to see the music signal and the heart activity. The blue and red plots contain the pulse wave information. On closer observation, a periodicity can be found that corresponds to that of the ECG signal.

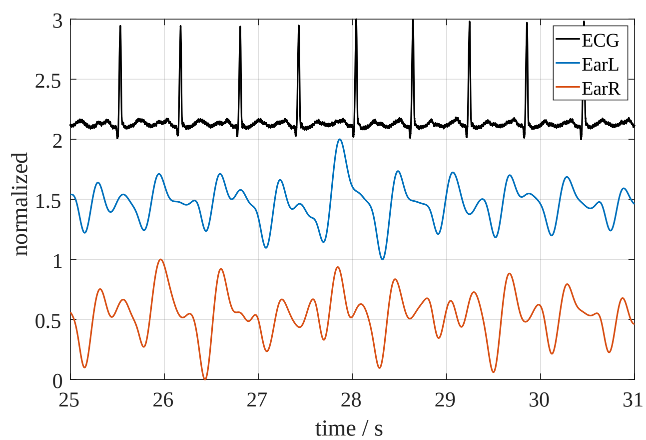

Fig. 7. Digitally processed measurement signals for a duration of 5 s.

V. CONCLUSION AND OUTLOOK

The system presented in this work has shown that the arterial pulse wave in the ear can be acquired while playing music using a conventional audio source and commercial headphones. The measurement circuitry and digital signal processing chain presented in this paper can be easily adopted in existing electronic systems without the need for new audio sources or headphones. One challenge with continuous pulse wave detection from the ears are the motion artefacts. However, it is conceivable that the robustness can be increased by combining both acquired audio channels. Considering this approach of signal fusion it must be taken into account that the signals from both ears can differ significantly in their shape. Since many electronic systems, such as smartphones, are equipped with motion sensors, it is also conceivable in future to identify situations with a lot of movement and exclude them from the measurement. However, for a precise analysis of the motion artifacts that can occur and the development of new algorithms to remove the disturbances, comprehensive data from subject measurements are first required. Another difficulty is ensuring that the ear canals are properly sealed. In the future, this can be achieved by designing headphone models that fit more precisely. In addition, the user could be informed if the measurement does not work due to poorly fitting headphones. In the future, extended measurements will be carried out with several test subjects, in which different headphone models will be compared.

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