Texas Instruments Innovation Challenge: Europe Analog Design Contest 2015

A Wearable Embedded System for Wireless Acquisition of Vital Parameters

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Qty.	TI Part Number & URL	Qty.	TI Part Number & URL
1	TPS63001	1	INA126E
1	TPS73025	1	OPA380
1	TPS72325	1	ADS131E06
8	LMV844	1	LMX9838

Picture of the team members

The measurement system

Project abstract:

This work introduces a novel wearable device with the focus to determine the arterial stiffness. The system is able to measure 4 microphone channels, a Photoplethysmography (PPG) signal, an Electrocardiogram (ECG), as well as acceleration of the subject with very high accuracy. Due to the high signal quality, it is able to measure small pressure changes in the sealed ear canal with modified analog microphone amplifiers. Additionally the heat sounds are detected inside the ear.
Via the analysis of the acquired signals, it is possible to determine a lot of vital parameters such as Pulse Wave Velocity (PWV), Pre-Ejection-Period (PEP) and Heart Rate Variability (HRV) relating to time. Furthermore, the system is in compliance with the IEC60601-1 safety requirements.

System Architecture

The block diagram of the developed wireless embedded system is shown in Figure 1. On the left side, the implemented measurement circuits are represented by the blocks. In addition to an Electrocardiogram (ECG) module and a controlled Photoplethysmography (PPG) circuit, there are four microphone amplifiers. The six analog processed signals are digitized with a 24-bit Analog-to-Digital Converter (ADC) synchronously by an *ADS131E06*. The digitized signals are sent to a 32-bit microcontroller, which is clocked with 120 MHz and is based on an ARM Cortex M4 core. The acceleration sensor contains an internal ADC, thus the data is transmitted directly to the microcontroller. After the real time signal processing using the internal Digital Signal Processing (DSP) core, the bio signals are transmitted via the BlueTooth module LMX9838 to a Personal Computer (PC) or a smartphone for further signal processing and to display the signals. For debug purposes, it is possible, to connect a PC via the Universal Serial Bus (USB) or the Universal Asynchronous Receiver Transmitter (UART). For long time measurements, the device is able to store the data on a microSD card.

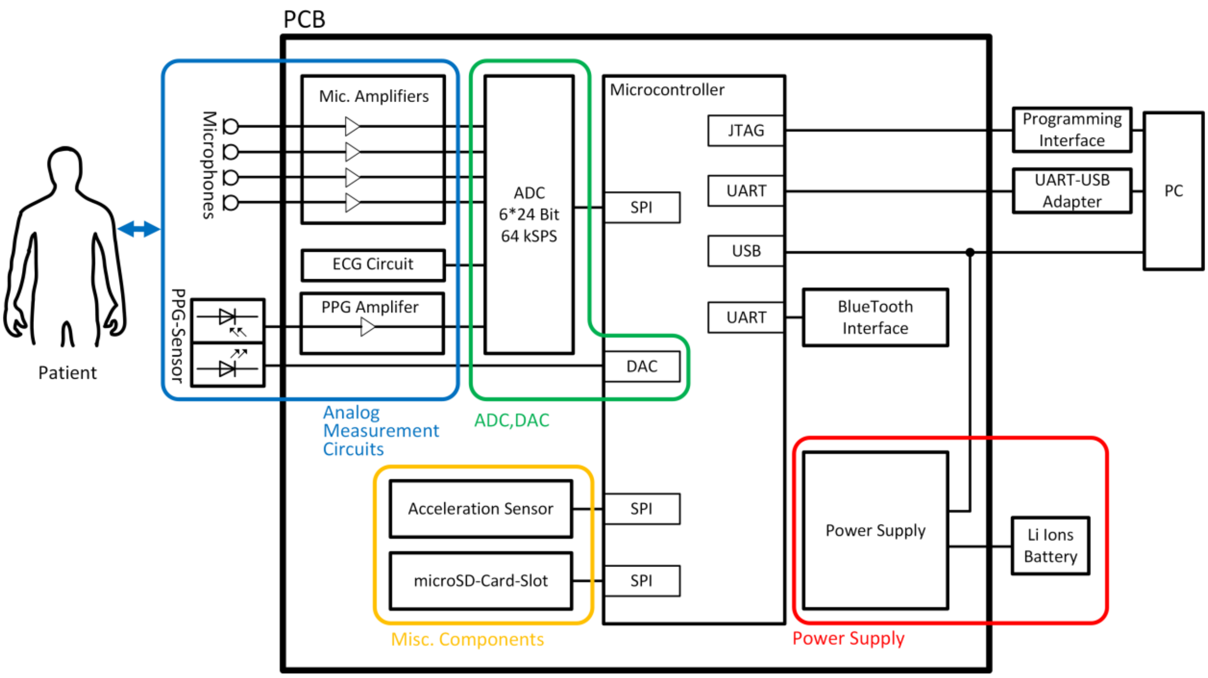

Figure 1. Block diagram of the developed embedded measurement system.

The developed device is powered by a lithium ions battery, which can be charged via a micro USB connector. Furthermore, the system is in compliance with the IEC60601-1 safety requirements.

Measurement Idea

Due to the pumping of the heart, volume and pressure changes occur in the arteries, which propagate with the Pulse Wave Velocity (PWV) of about 4…12 m/s through the human body. Since this value changes depending on the stiffness of the arteries, it is a very important prognostic marker for cardiovascular diseases. Nowadays, it is usually measured by assuming the ECG signal to be the starting time of the pulse wave at the heart and detecting the arrival time at different positions by using cuffs. By estimating the distance between the heart and the pulse wave arrival point, the averaged PWV is calculated. One disadvantage of this method is the variable Pre-Ejection-Period (PEP), a time delay between the electrical stimulation of the heart and the ejection of blood.

In this work, an embedded system is developed for proving a new measurement method, which uses the heart sounds as starting time of the pulse wave instead of the ECG. Additionally the arrival of the pulse wave is determined by measuring pressure changes in the ear canal, which is simply sealed by a standard stethoscope earplug (Figure 2). Finally, the measurement of the heart sound will also be executed inside the ear canal with small electret microphones. Thus, just one measurement point is necessary in comparison to all the other devices in the market using two-point measurement system.

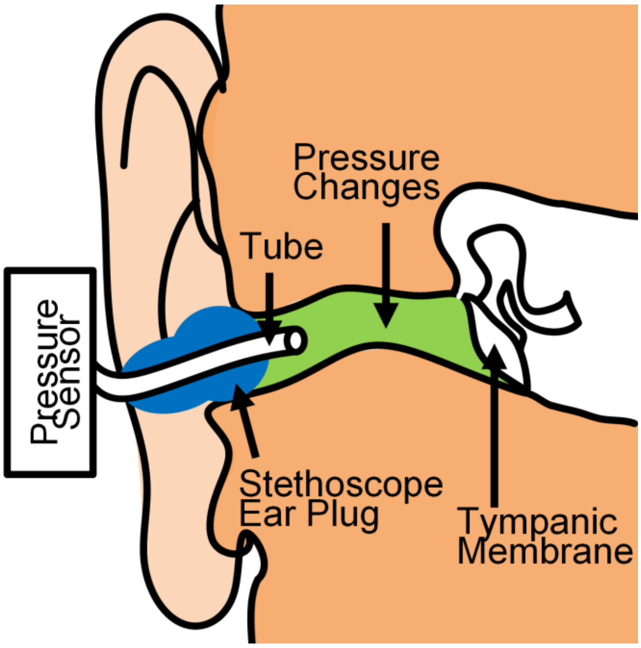

Figure 2. Measurement idea to determine the pressure changes inside the sealed ear canal due to the arrival of pulse waves.

Theoretical Background

The Electrocardiogram (ECG) reflects the electrical activity of the heart. The acquisition of the ECG signal is performed simply by using two electrodes on the patient´s chest and one on the leg. Usually the signal frequency components are in a range of about 0.5 Hz to 150 Hz.

The Photoplethysmography (PPG) is a measurement method to determine the volume changes of blood inside a tissue. Due to the blood pulsations, the reflective

behavior of tissue changes with the rhythm of the heart and the morphology of a pulse wave. This can be detected by applying a light source on the skin and measuring the reflected light close to the light source.
Heart Sounds (HS) occur due to the mechanical interaction between the heart and blood during the pumping cycles.

Implementation

Microphone amplifiers: Since these amplifiers will be used to amplify the heart sounds ($f \approx 20 \ldots 50$ Hz) as well as pressure change signals, caused by the pulse wave ($f \approx 1 \ldots 20$ Hz) at the ear, the circuit has to be variable. It has to be additionally guaranteed, that the amplifier and filters do not change the phase of the pulse wave too much. Otherwise, errors will occur in following timing calculations.
Generally the circuit consists of a passive high pass ($f_{cutoff,HP} \approx 20$ mHz), a non-inverting amplifier (gain = 1) and a passive anti-aliasing filter. Since the Op Amp can produce higher output voltages, than the ADC tolerates, protection diodes (D301) are used. Because of its rails, a bipolar 2.5 V supply for the Op Amp would avoid the use of the full ADC input range. The schematic is shown in Figure 3.

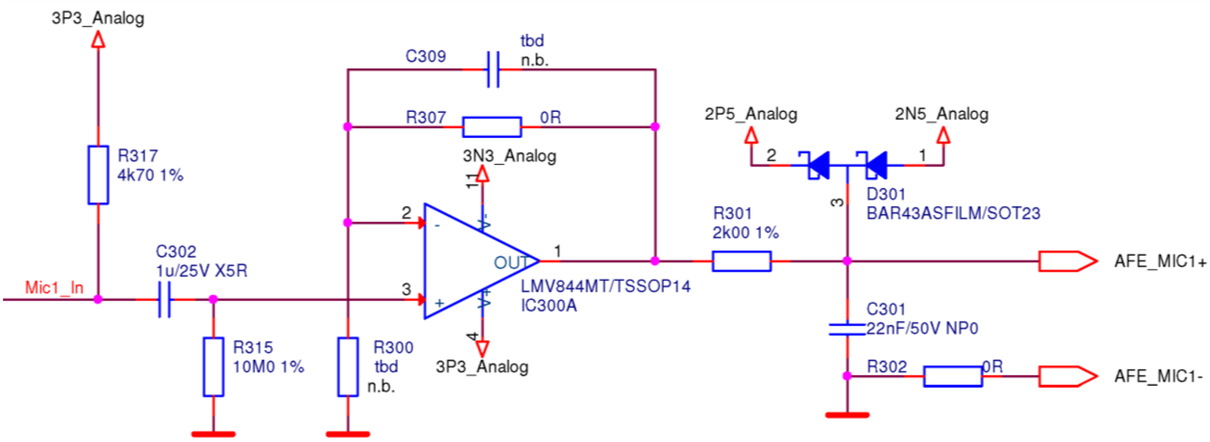

Figure 3. Schematic of one microphone amplifier. Three further amplifiers of the same kind are implemented on the PCB.

It can be proven, that choosing resistors with tolerances of 1 % and capacitors with tolerances of 5 % leads to phase shifts of less than 0.1° in a frequency range of 0.5 Hz up to 50 Hz. The reason for using the LMV844 are its low output rails and the input voltage noise of $20\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$.

ECG circuit: The differential voltage measurement of the ECG circuit is realized with an Instrumentation Amplifier (INA). The INA126 has the ability to adjust the amplification with an external resistor. As it can be seen in Figure 4, this amplification resistor is divided into R405 and R406. Thereby the signal´s common mode can be fed back for shield driving and for the Driven Right Leg (DRL) circuit.

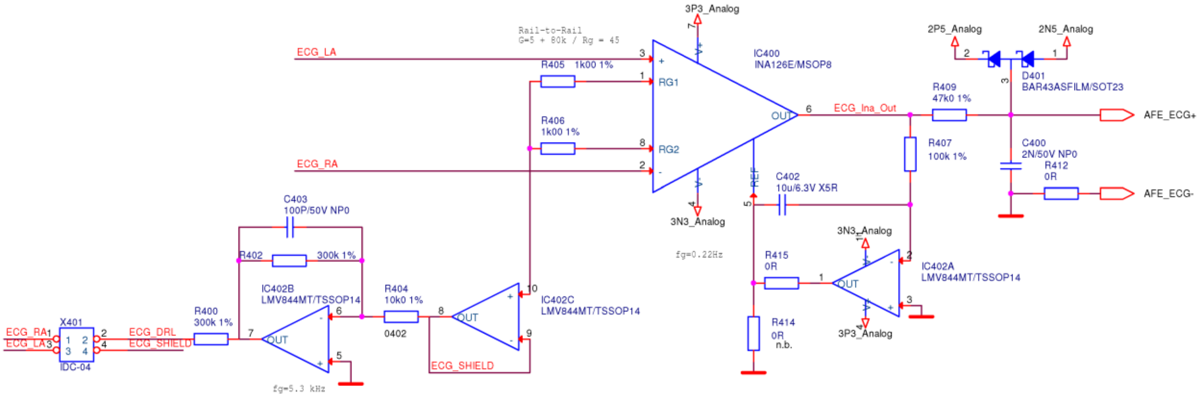

Figure 4. Schematic of the ECG circuit.

For this application, the INA126 is excellent because of the very high input impedance of $10^9\ \Omega$ and the low input bias current. The availability of four LMV844 in one TSSOP14 housing is a major advantage for this wearable device.

PPG module: In this application, the Photoplethysmography (PPG) delivers an additional time reference, which could be interesting, but not strictly necessary. Thus, the circuit (shown in Figure 5) is developed as simple as possible. Instead of using many analog components for eliminating the DC offsets (about 99.9 % of the PPG signal), the advantage of the very high resolution ADC (ADS131E06) is taken. In theory the loss Q_{loss} of resolution is about $Q_{loss} = -\log_2(1-0.999)$ bits ≈ 10 bits. In the ideal case, there are 14 bits of resolution left for the PPG signal´s information.

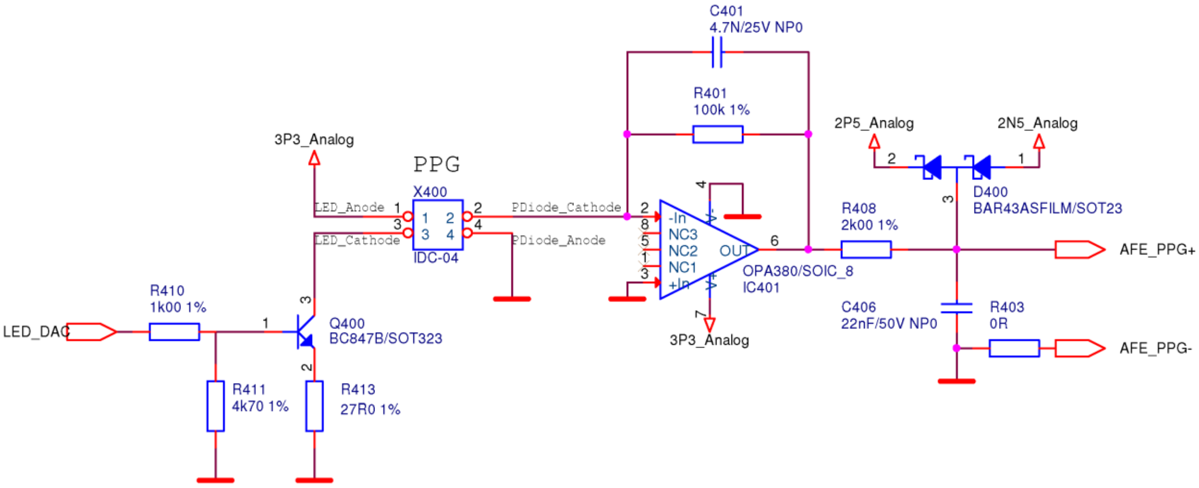

Figure 5. Schematic of the PPG module. The schematic is kept very simple to reduce the number of needed components.

The OPA380 is a transimpedance amplifier, especially for this photodiode monitoring. To adjust the LED´s brightness, an internal Digital-to-Analog Converter (DAC) of the microcontroller is used.

Digitalization: The ADS131E06 digitizes all analog signals for the followed digital signal processing. The very high resolution of 24 bits is especially useful if there are small signals with high offsets like the PPG signal. Of course, the higher the quality of the digitalization is, the less computational effort is usually afterwards necessary, to improve the signal. In Figure 6 the circuit diagram is shown.

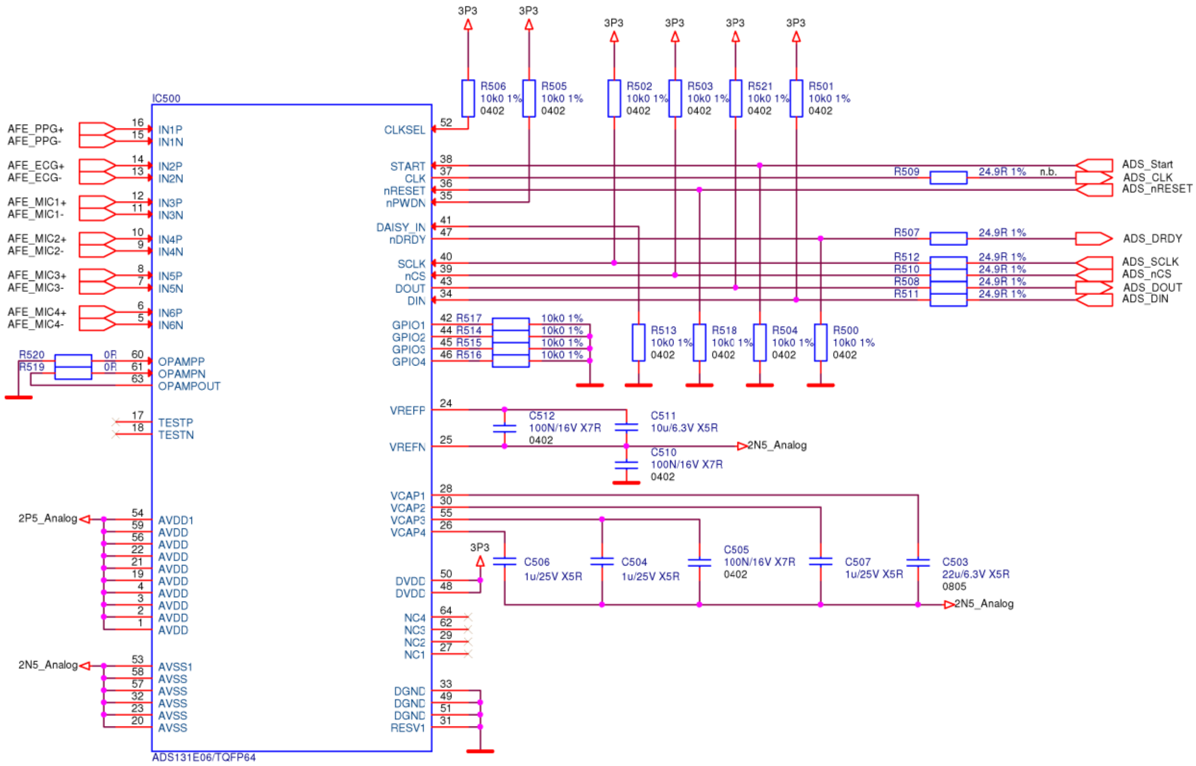

Figure 6. Connections of the ADS131E06 analog to digital converter.

The ADS131E06 is able to digitize up to 6 differential channels synchronously. This is very important for timing measurements, as in this application.

Power Supply: The developed device can be powered by a Li Ions battery or for debugging via a microUSB connection. Commonly the battery is charged via a charge regulator, when the device is connected to USB power, as shown in Figure 7. To generate a stable voltage of 3.3 V, the DC/DC converter TPS63001 is chosen. Due to its efficiency of up to 96 %, the battery life time is much higher than by using other ICs. For generating the negative power supply, a voltage inverter IC is used. Since the ADC needs to be powered by ±2.5 V, both voltages have to be reduced by Low Drop Out (LDO) voltage regulators. Because of the very low power consumption of the ADS131E06, the currents through the LDOs are very low, which leads to acceptable power consumptions of the LDOs.

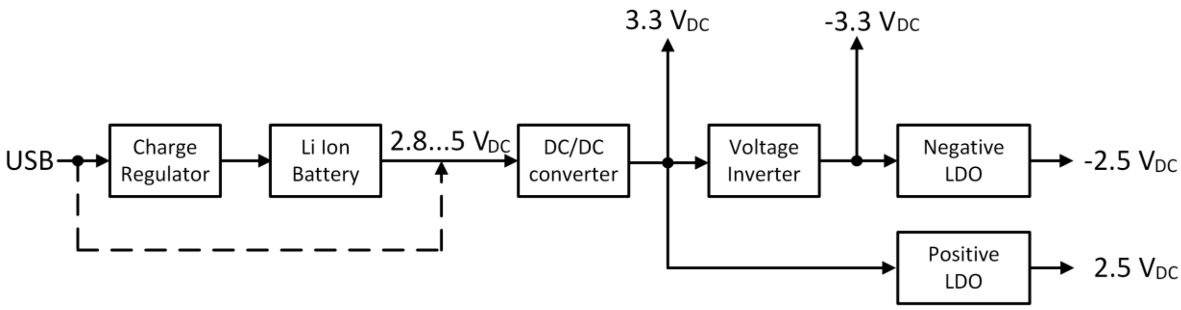

Figure 7. Block diagram of the system´s power supply. In the implementation, the voltages are additionally divided into "digital" and "analog" supplies.

Manufactured Prototype: After developing the schematic with the help of TI Filter Pro Desktop and executing SPICE simulations with Cadence OrCAD, the PCB layout was designed. For that, the tool Cadance OrCAD PCB Editor was used. To keep the PCB as small as possible, and to avoid crosstalk between fast signals, a 6-layer PCB was developed. Further shrinking was made possible by populating the PCB from both sides. The assembly of both sides is shown in Figure 8. It can be seen, that there is an unpopulated part under the BlueTooth module. This is according to the datasheet of the LMX9838 necessary. At the bottom of Figure 8, a photograph of both sides of the manufactured PCB is shown. To get a better impression for the dimensions (61 x 37 mm²), a 9 V block battery is illustrated aside. Finally, the PCB contains more than 200 components.

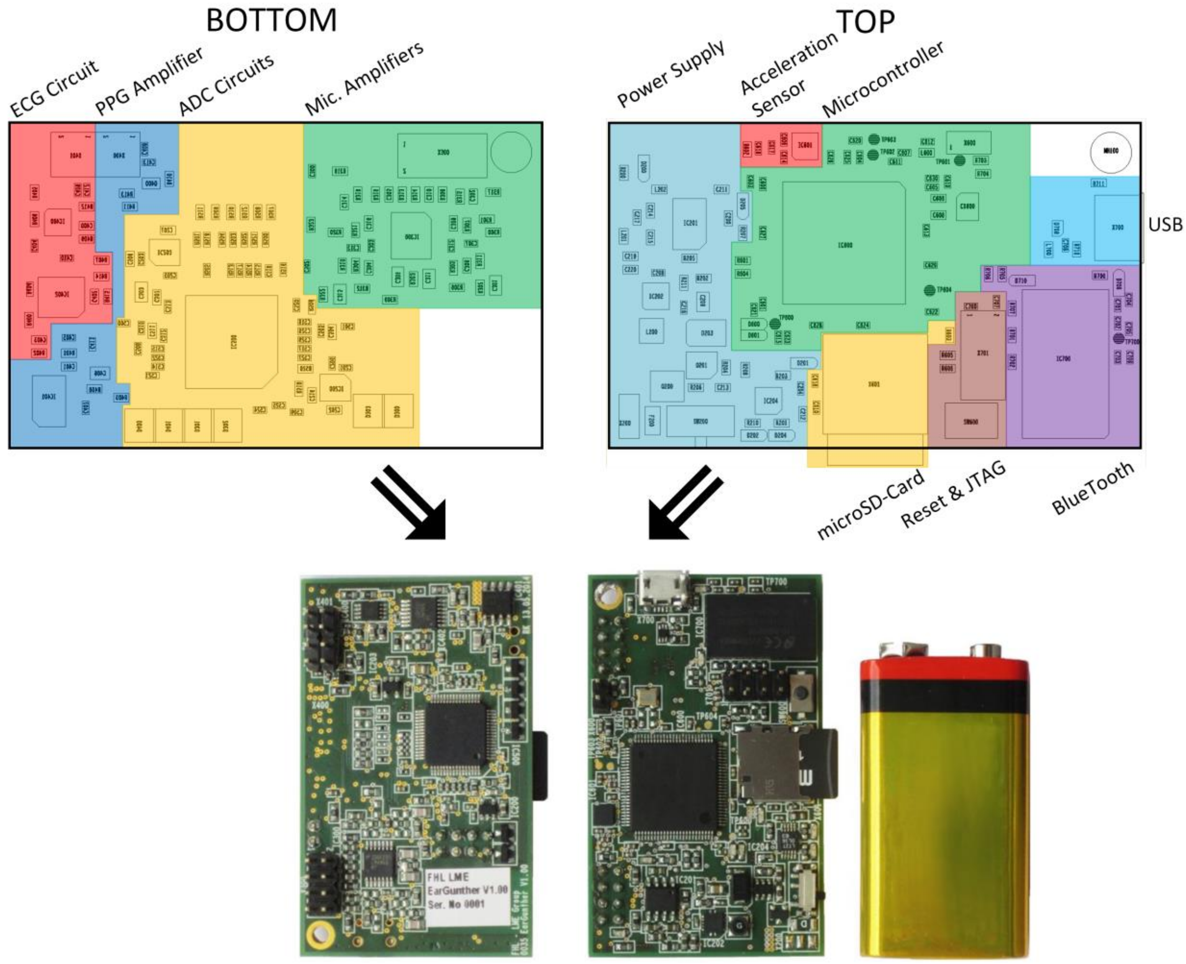

Figure 8. Developed prototype of the measurement device. The 6-layers PCB contains more than 200 components and is populated from both sides. The 9 V batterie is just shown to compare the dimensions (61 x 37 mm²) of the PCB.

Experimental Results

In Figure 9, the first measurements, acquired with the developed system, are shown. The ECG and PPG signals are not filtered just normalized. In the ECG plot, the typical morphology of ECG signal of a healthy person can be seen. As calculated before, the PPG has an effective resolution of about 14 bits, which is still very good for analysis. In the upper right plot, the pressure changes inside both ear canals are shown. Since the human body does not have mirror symmetry, there is a small time shift between the pulse wave arrival times. This is just measurable, because all ADC channels of the ADS131E06 work independently and synchronized. The lower right plot shows very hard filtered (FIR bandpass, designed by The Mathworks MATLAB Filter Toolbox) heart sounds. The green signal was acquired on the chest and the red plot was acquired with a microphone inside the ear canal. It seems that the heart sound is detectable inside the ear with this kind of signal processing.

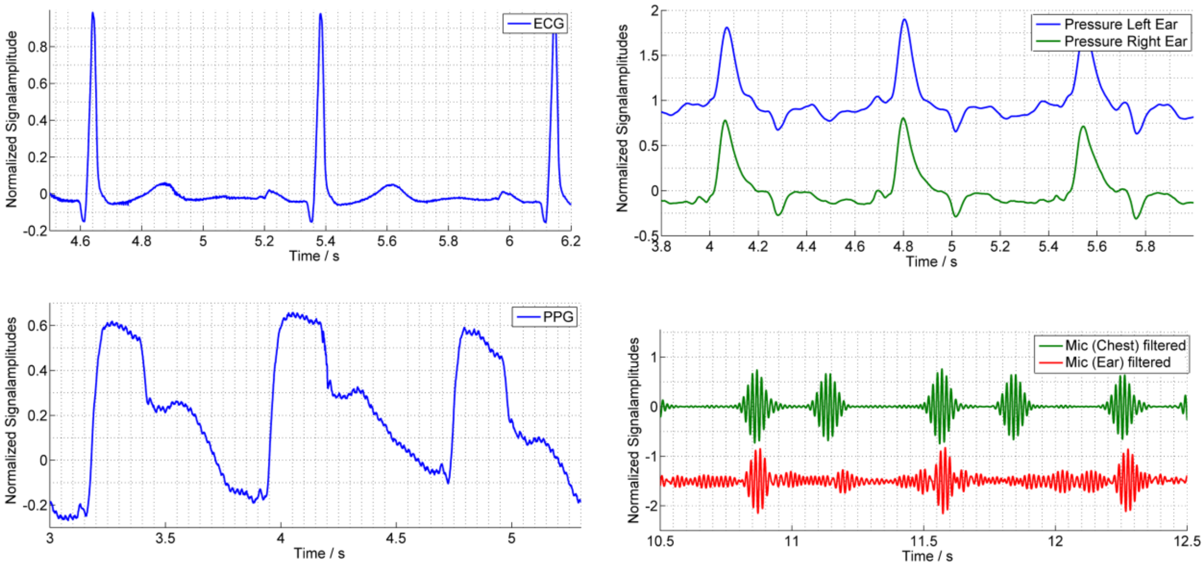

Figure 9. First measurement acquired with the embedded system. In addition to an ECG and a PPG signal, the pressures in both ears are measured. The heart sound taken from the chest and inside the ear is shown, too.

Using a MATLAB algorithm to detect both, the heart sounds and the pulse wave depending pressure changes inside the ear canal leads to Pulse Wave Velocities of about PWV ≈ 5.8 m/s. In comparison with literature values, this is quiet realistic.

Summary and Outlook

An embedded wearable system to acquire vital parameters from the human body was developed and first measurements to prove its functionality were executed. In contrast to common wearable, battery powered devices, the system´s focus is the determination of the arterial stiffness.

The device is able to measure an ECG, PPG, acceleration and four audio sources synchronously with a high resolution ADC. After digitizing, the microcontroller transmits the data wireless to a PC or smartphone for signal processing and analyses.

First measurements showed that the system can be used to record bio signals in an excellent quality. Because of this behavior, it is possible to detect the heart sounds for example inside the ear canal.

In the future, the digital signal processing has to be optimized to get more information out of the data. This could be realized with the DSP core of the microcontroller.