Digital stethoscope system – the feasibility of cardiac auscultation

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ABSTRACT

The application of the digital stethoscope system is a new tendency in methods of cardiac auscultation. Heart sounds, generated by the fluctuations of blood velocity and vibrations of muscle structure, are an important signal in the primary diagnosis of heart diseases. Since the XIXs century for physical examination an analog stethoscope was used, but the development of microelectronics enable the construction of digital stethoscopes which started modern phonocardiography.

The typical hardware of the system could be divided into analog and digital parts, respectively. The first one consists of microphone and pre-amplifier. The second one contains a microcontroller with peripherals for data saving and transmission. Usually the specialized software is applied for the signal acquisition and digital signal processing (filtering, spectral analysis and others).

This paper presents an overview of methods used in cardiac auscultation and expected developing path in the future. It also contains the description of our digital stethoscope system, which is planned to be used in poliphysiographical studies.

Keywords: heart sounds, stethoscope, digital signal processing, phonocardiography

1. INTRODUCTION

1.1. Background

Cardiac auscultation is one of the most important physical examination and a part of the first medical diagnostic procedures. It evidences many pathologies of the heart structure such as valvular heart disease, coronary heart disease, arterial disease and artificial heart valve performance (mitral regurgitation or aortic stenosis) [1]. It reflects the heart and cardiovascular mechanical condition. Many of the heart diseases can be recognized in the primary stage using heart sounds auscultation and therefore are treated earlier. Irregularities detected during auscultation begin the therapy. Compared to the traditional ECG, this method provides information before the symptoms will be recognized in ECG and before patient starts to feel pain [1]. In addition it is non-invasive and reproducible and inexpensive method.

There are several conditions, which should be satisfied to make this method diagnostically useful. Firstly, the heart sounds must be strengthened. After the acquisition it is needed to use filters, because of the presence of noise, especially from the extrinsic environment [2]. Also researches tried to improve signal-to-noise ratio [3]. Furthermore the specification of the signal is dependent on the different location of auscultation points [4], so the device parameters must be adjusted. To achieve the desired results, signal should be processed. Further it requires automatic incident detection, in order to simplify initial diagnosis performed by people without medical knowledge [3]. Because of the development of the telemedicine, digital device should be prepared for the wireless communication with the medical consulting system [1]. In addition, the human ear has low sensitivity in frequency region where heart sounds are found, therefore it is necessary to construct the highly sensitive device. At present, the real-time acquisition systems are very useful and that is a possibility to build a digital systems dedicated for a home care. Also it gives a chance for small medical centers to diagnose heart diseases without having highly expensive equipment [4].

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1.2. Acoustic signal generation

Heart sounds are the acoustic waves generated by the beating heart and resultant flow of blood through it. It is a mechanical vibration caused by the myocardial systolic/diastolic, valve opening and closing, blood flow impact in ventricular wall and large artery in the heartbeat cycle.

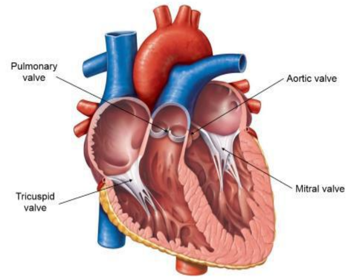

Figure 1. The cardiac structure

The entire signal is contained in a wide range of low frequencies, described as a 5-600Hz [3] or 50-500Hz [1]. Above 120Hz is usually considered as high-frequency sound, 80Hz-120Hz as a middle-frequency sound, below 80Hz as a low-frequency one.

There are two normal heart sounds (in healthy adults) described as a “lub” and a “dub” and called the first (S1) and the second (S2) heart sound. From physiologically point of view their occurrence is normal. In addition, a variety of other sounds may be presented including heart murmurs, adventitious sounds, and gallop rhythms S3 and S4. They might or might not be a symptom of disease.

First heart sound (S1) is produced by the closing of the atrioventricular valves during the beginning of the ventricular systole. It occurs as a result from reverberation within the blood associated with the sudden block of flow reversal by the valves. This bass tone is about 40-60Hz frequency and continues to about 0.14-0.16s [2].

Second heart sound (S2) is a second component of a heart beating, produced by the closing of the semilunar valves. It is called a diastolic tone, because it occurs during the diastole of the ventricular muscle. The second heart tone is a vibration of frequency of 60-100Hz and continues to about 0.08-0.12s.

Sometimes can be heard also the third (S3) and the fourth (S4) heart sound. The third heart sound occurs in some healthy children and young people. It is a signal of frequencies from the range of 10-50Hz. The same range describes the fourth heart sound. It could be heard in the body of healthy individuals over the age of 40.

In analysis of the heart sounds other parameters, such intervals between S1 and S2, between S2 and S1, heart sound gap period, have an important value. Their duration varies with age and might be a symptom of a disease. The average heartbeat cycle of adult is about 0.8s, which includes 0.3s systole and 0.5s diastole. The time proportion of S1-S2 interval and S2-S1 interval is about 1:2 [1].

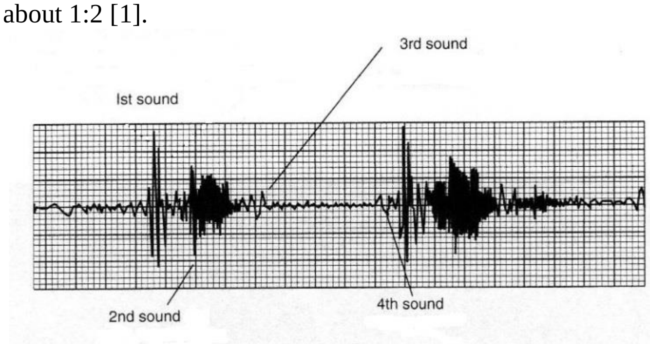

Figure 2. Typical waveform of the heart sounds (adapted from [14])

The other component in the heart sounds signal are the heart murmurs. They are blowing, whooshing or rasping sounds as a result of vibrations caused by turbulent blood flow patterns. They perform at different frequencies (even to 1000Hz) and at different moments in heart beating cycle. It is very important to distinguish the heart murmurs and determine their clinical significance, because it could be a syndrome of disease or might be a physiological signal (innocent murmurs).

1.3. Methods of measurements

The heart sounds signal could be measured in two ways, with analog or digital stethoscope or by phonocardiography. Stethoscope is simple tool to transmit the heart sounds from the chest wall to the ear, but it is not easy to use it correctly. Firstly the human ear is not sufficiently sensitive to determine all frequencies (different level of auscultation skill) and some components of signal can be omitted. Secondly to make of the diagnosis is required a long time-practice and experience of the doctors [3,6]. Also the signal from an acoustic stethoscope has very less sound amplification [5]. Therefore, it was a need to design a device, which could make an automatic recording and interpretation of a signal.
Phonocardiography (PCG) is a main tool showing the timings and relative intensities of the heart sounds with graphic recordings on the paper.

The digital stethoscopes with a suitable software allowing automatic analysis of the signal could be more widely distributed diagnostic tool.

2. METHODOLOGY

2.1. Schematic diagram of the digital stethoscope system

Figure 3. shows a schematic diagram of the digital stethoscope system.

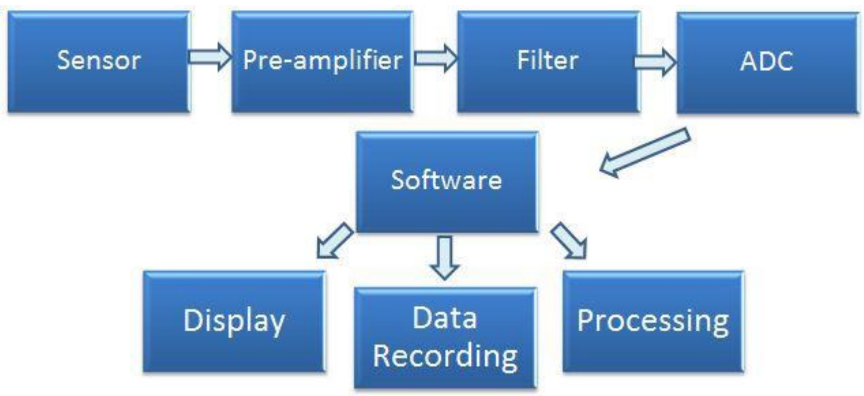

Figure 3. Schematic diagram of the digital stethoscope system

In this paper we try to systematize recommendations regarding the construction of the digital system, which should be observed to achieve the high quality recording and processing of the heart sounds. Digital stethoscope system consists of a sensor, which receives a signal from the chest, a preamplifier, to strengthen sounds, then a filter and analog to digital converter. Data are transmitted to the computer by a cable or wirelessly. Then the signal samples are processed to feature extraction and classification. After that an automatic diagnose could be made.

2.2. Sensor

The first component of the digital stethoscope system is a sensor, which is able to capture the heart sounds from the places on the chest. It is difficult, because the signal has a low amplitude and it is an acoustic signal, so during the recording is a huge noise from the extrinsic environment. For this reason signal filtering and processing is required.

In most of cases to record a heart sounds the stethoscope is used. It has two important characteristics, one is the enlargement of the sound and the other excludes environmental noise [9]. However, analog stethoscope has a very small sound amplification [5] and it cannot register data in the memory. The digital stethoscope might be the good solution.

The main companies which manufacture stethoscopes are the 3M Littman, Welch-Allyn and Think-labs. They differ in functionality and design methods, for examples Welch-Allyns stethoscope has piezoelectric crystal at the head of a metal shaft, while Think-labs one use a stethoscope diaphragm with an electrically conductive inner surface to form a capacitive sensor. Digital stethoscopes has a lot of different functions, which helps the doctors to obtain a more accurate diagnose. They can amplify signal, register data on the memory card or transmit data to the computer using wireless technology. Also they have a special algorithms, which can be used to reduce the noises, like Ambient Noise Reduction (ANR) technology in Littman's stethoscopes [17]. Digital stethoscopes are the most popular detectors which are used in a system of the heart sounds auscultation, especially when the researchers concentrate on the signal processing [1-5].

However there are other solutions to obtain the raw data. In many cases, the detector of an analog signal is a microphone. It could be used with an analog stethoscope (after the chest piece) and after the digital, but it is also possible to record a heart sounds only using a microphone. It is important to define a suitable features of it. Range of frequency must be adjusted to parameters of signal (30Hz – 10000Hz [3]), sensitivity about 6mV/Pa (-44dB) [7], -46dB[3], impedance 2kΩ. In cardiac auscultation small, piezoelectric microphones are commonly used [3,5,9].

At present there are also PVDF (Polyvinylidene fluoride) sensors research, which can be applied as a detector of vibrations caused by beating heart. It is a piezoelectric plastic material having a homogenous and solid structure, which is useful, especially in the measurements of physiological pulsatile signals. In [6] there is a comparison of the results from a PVDF film sensor and, as a reference, from the microphone, which were considered as promising.

2.3. Preamplifier

Signal from the microphone or other recorder is not suitable strength, so it must be amplified in pre-amplified circuit. When in the research are used a digital stethoscope, this component was not necessary. But in the systems, which are made from the basics, different amplifiers was implemented.

In that circuit the most important element is an operational amplifier, which should be low noise, have high slew rate and voltage gain. Besides that in usage there are passive elements such like capacitors and resistors to adjust sensitivity and amplification.

In [5] they applied a circuit a LT1115, which is a ultralow noise, low distortion, audio op amp. It is used in applications like high quality audio preamplifiers or low noise microphone preamplifiers. In another solution [7] applied INA122 – the low-noise precision microphone preamplifier. In [9] was also used amplifier, the same as in [18] with the gain of 1000. In our construction we have implemented other op-amp – LF356 and TL072, which have all the required parameters.

2.4. Filter

It is necessary to filter the signal from the preamplifier to eliminate frequencies besides the range of heart sounds. Also it is required to discriminate many unwanted factors such as breathing noise, artifacts, voice and external noise.

There are two ways to apply the filter. First is to build an analog filter with using an operational amplifier, resistors and capacitors. Good method is to use the Sallen-Key topology and a TL082 amp to construct a high order active filter. We chose the fourth order filter with a cut-off frequency equals 1000Hz in order to save a heart sounds and murmurs bandwidth. On the other hand most of the researchers used a digital filters implemented in the software writing e.g. MATLAB® [5], after the analog-to-digital converter.

In [1] was used an IIR digital elliptic lowpass filter which removes the high frequencies over 800Hz, where the cut-off frequency equals 790Hz, the maximum passband attenuation equals 1dB, stopband start frequency equals 800Hz, the minimum stop band attenuation is 50dB. In [7] researchers implemented a bandpass filter in the range of 35Hz to 200Hz. In [6] there is an application of a digital Butterworth fifth order bandstop filter to eliminate 60Hz frequency and the same band pass filter with range from 40Hz to 60Hz like in [10].

2.5. Analog to digital converter

To processing the signal in the software, analog to digital converter is needed. Researchers applied different method to save the data from the analog circuit. When we use an ADC, two features are important. Firstly, the sampling frequency, which must be adjusted to the range of a signal and take into account the assumptions of the Nyquist–Shannon sampling theorem. Secondly, the sampling resolutions, which determines the precision of stored samples.

In [3] was used an IC recorder with a sampling frequency 44,1kHz and 16 bits sampling resolution. Then signal was transmitted into a computer by USB interface. Constructors in [7] digitalized signal by a notebook computer with sampling rate of 11025Hz and 16 bits resolution. In circuit with PVDF sensor, 1000Hz sampling frequency was used [6]. When researchers used an electronic stethoscope, sampling frequency was 22050Hz. In experts system from [12] was installed 12-bits ADC card. As the heart sounds are the acoustic signals, in many cases researchers used a soundcard which is normally available with all the computer types [18]. Also as a soundcard was implemented a virtual machine in the software like LabView® [11].

In most of the applications the analog signal was transmitted to the computer and then convert to digital form. However, it is also another method, without using PC. Microcontrollers are very popular tool, because they have a built-in ADC and can control the transmission signal to other device or the processing signal with using digital signal processing (DSP). We implemented STM32 – microcontroller with the ARM core processor. ADC has a 12-bits resolution and was used at 2000Hz sampling frequency.

2.6. Software

The aims of software are: to display the heart sounds in real-time, to record and saved data and to process the signal [12,16]. In all of these tasks we can use microcontroller, PC computer or even both.

2.6.1. Display

Display of signal in the real-time is a difficult procedure [2]. If the digital data are in computer, which is also a tool for display, only some algorithms are required to show a true waveform. However, if data are converted in microcontroller is needed to transmit it. We can use wireless transmission via for example Bluetooth® interface [15] or with using a cable (RS232, USB) [12].

2.6.2. Data recording

Recording of the data is needed to offline analysis of a signal and may be used in telemedicine, when previously recorded patient data is used in later diagnosis by a physician. Signal samples can be saved on the computer after digitalization or when it is used a microcontroller, can be saved on the SD memory card.

2.6.3. The signal processing

Signal processing is the most important element of the system, because it provides information useful for diagnosticians. Its purpose is to de-noise and make segmentation of the signal, features extraction and classification between the normal and abnormal heart sound [4].

To de-noise signal we could use methods in time-frequency domain, such like wavelet transform [3,7]. In [2] they used for example frequency division with a db3 wavelet function.

Automatic segmentation of the heart signals into individual cycles provide information such as the S1, S2, systolic and diastolic durations. Special algorithms implemented in MATLAB® enable automatic detection of these events. In some research ECG as a reference is used [9]. In other method is applied a Wavelet multi-resolution analysis [13].

The most effective features extractions methods are the time-frequency analysis. In [2] was used a wavelet decomposition and reconstruction, which allowed to get all parts of frequency components of the signal. In experiments also was made an envelope extraction by used a wavelet transform and Hilbert-Huang transform [1]. In [3] to extract is applied a vibration model of single degree-of-freedom. Research about time-frequency analysis describe different methods of signal preprocessing from FFT to continuous wavelet transform and the latest method is recognized as the best [8].

On Figure 4. is presented a normal heart sounds, spectrogram and result of wavelet transformation [5]. It is clear that spectrogram is not a sufficient method to detect events, while the wavelet transform allows accurate extraction of heart sound. It seems that this method has a great potential in the heart sound signal processing [5].

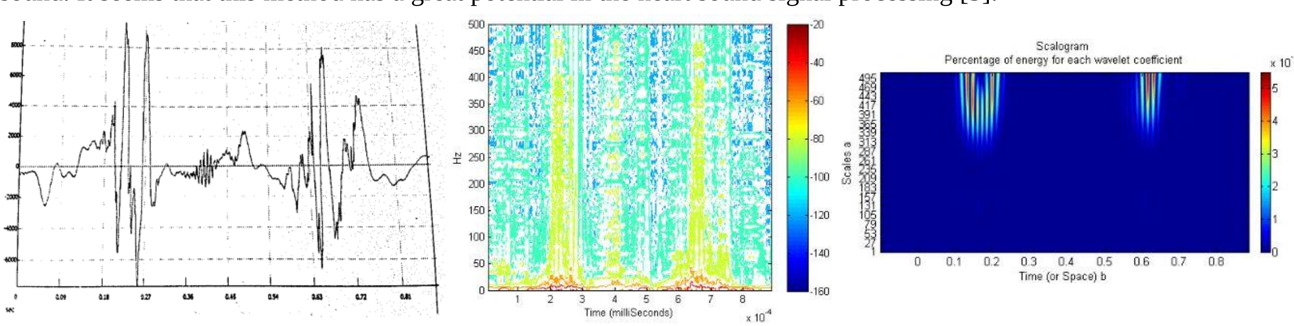

Figure 4. Spectrogram and result of a wavelet transformation of a normal heart sound (adapted from [5])

In many cases it is required to do an automatic detections of normal and abnormal heart sound. It can be done using methods such as implementation of a neural network, Mel-frequency cepstrum coefficients (MFCC) or Hidden Markov Model (HMM). In [2] was used a Takagi-Surgeon type fuzzy neural network to classifier of heart sound. Researchers from [4] applied MFCC. It is a very popular method used in recognition of a speech. As heart sound and speech are both acoustic signals, it is a good idea to use MFCC in heart sound recognition and identification. HMM in [4] was based on results from MFCC.

2.7. Research systems

In different configurations researchers tried to design and build a system, which meets all the required assumptions.

2.7.1. Digital stethoscope system using Hidden Markov Model

Figure 5. presents one of the idea of building system [4], but most of the components describe a digital processing. In it the signal recording by a phonocardiography sensor is then amplified with preprocessing circuit. Next one step is to digitalized it and stored. Subsequently this data undergo segmentation and feature extraction. System is be able to make a decision about normality of a heart sound by using Hidden Markov Model (HMM).

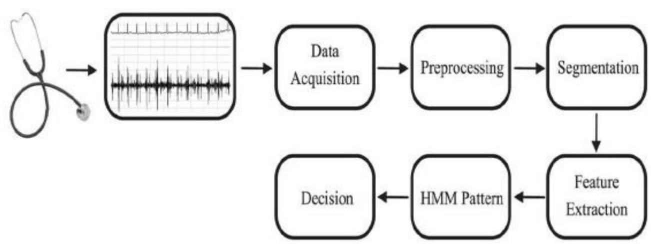

Figure 5. Schematic diagram of acquisition system (adapted from [4])

2.7.2. Heart sound recording system

On the Figure 6. is a simple diagram of a system presented in [3], which consists of an analog part to record signal and with digital to analysis and display waveform. Chest piece is a component of electronic stethoscope (Littman). Then signal is recorded by a microphone (AT805F) and by a IC recorder (Olympus, Voice-Trek V-51). It is a possibility to hear it by an earphone or it might be transmitted to the computer. Signal processing is implemented in MATLAB®.

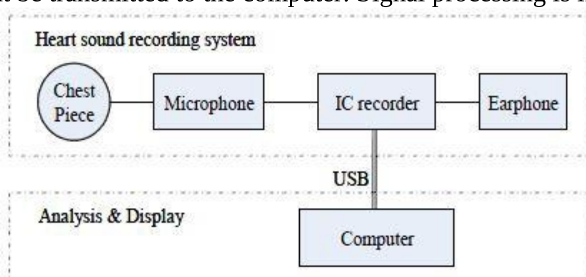

Figure 6. Schematic diagram of recording and analyzing system (adapted from [3])

2.7.3. Low cost digital stethoscope system

System on the Figure 7. is a simple probe of making a good resulting digital stethoscope system with a low costs [5]. The electronic stethoscope houses a SONY ECM microphone. It is connected to a pre-amplifier circuit, where is used a LT1115 operational amp. All this components are closed in a plastic box. Then signal goes to the PC, where is processed by MATLAB®, Sigview, Goldwave and Multisim.

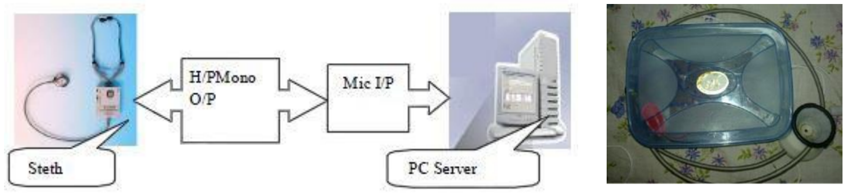

Figure 7. Schematic diagram of the low costs digital stethoscope system (adapted from [5])

2.7.4. Digital stethoscope system for fetal phonocardiography

On the Figure 8. is presented schematic diagram of a processing digital signal to obtain a FHR (fetal heart rate) ratio [7]. Two signals (abdominal channel and external channel) are de-noised and segmented by a bandpass filter. Then an extraction of envelope is used. Further components of the system are applied to search a S1 and S2 burst, which is necessary to obtain a FHR.

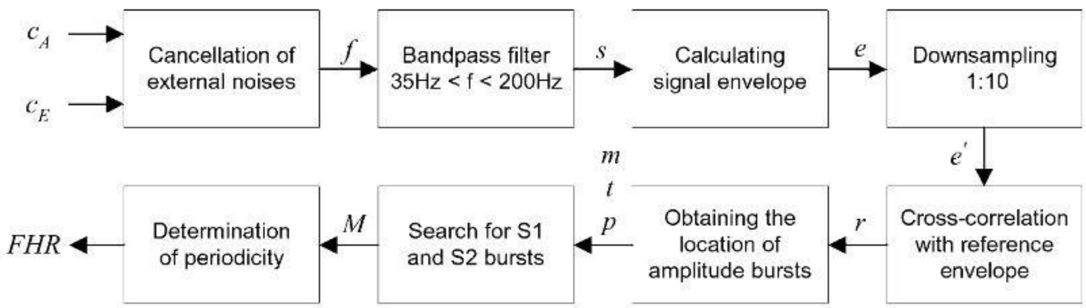

Figure 8. Schematic diagram of signal processing in digital system (adapted from [7])

3. DATA

Our realization of the digital stethoscope system consists of a microphone, preamplifier, filter and ADC in microcontroller. Results of the acquisition heart sound signal was store on SD memory card. Data were recording at different places on the chest, dependent on subjective strongest signal location. In our system the study was registered from the young healthy adults.

4. RESULTS

As a results we want to present our design and construction of the digital stethoscope system, which meets mentioned above assumptions. The system allows data recording on the memory card and performed the simple signal analysis.

4.1. Schematic diagrams of the configuration of the system

We built the digital stethoscope system, which consists of an analog and digital part, connected with a wireless transmission.

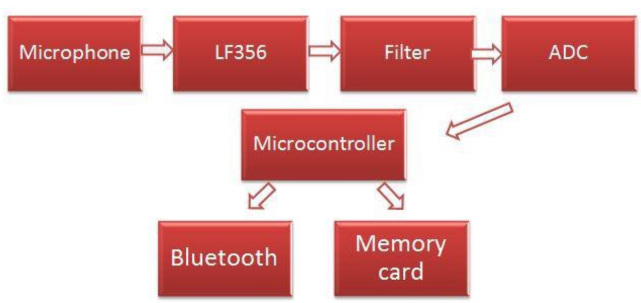

Figure 9. Schematic diagram of our digital stethoscope system

An analog part is used to recording data from the chest of patient. Main sensor is a capacitive microphone with a -44dB sensitivity. Then signal is amplified in amp circuit with LF356. We applied a downpass filter with a cut-off frequency equals 1000Hz. Signal, after adding the DC component to move it to the range of nonnegative values, is converted in ADC in microcontroller STM32. Digital samples are next transmitted to the PC with using Bluetooth® interface and subsequently, stored on the SD memory card. Using MATLAB applications the graphic waveform was present and signal was processed by wavelet transform. In the future system can be enriched with a more advanced processing procedures.

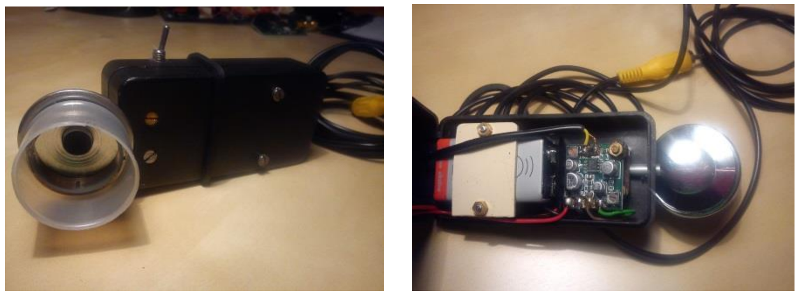

Figure 10. The images of our constructed device (two projections)

4.2. Results of acquisition and signal processing

Figure 11. contains the analog waveform of heart sounds visualized on oscilloscope (top) and the same signal after digitalization in our system (bottom).

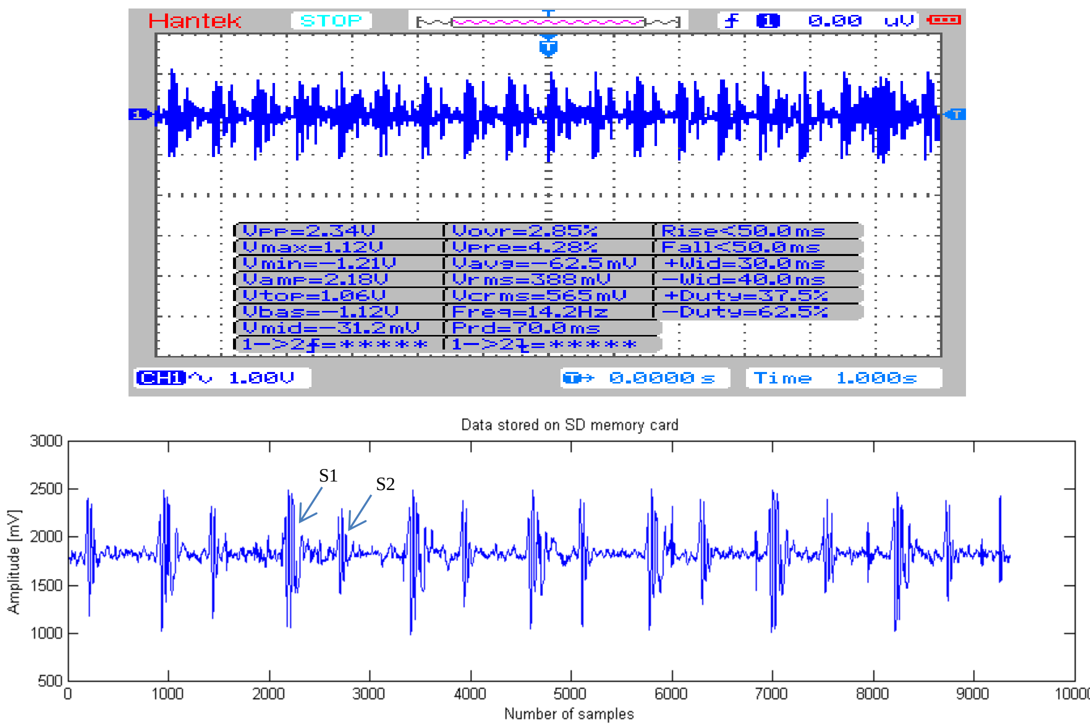

Figure 11. The waveforms from the analog circuit (top) and recorded by digital part of the system (bottom)

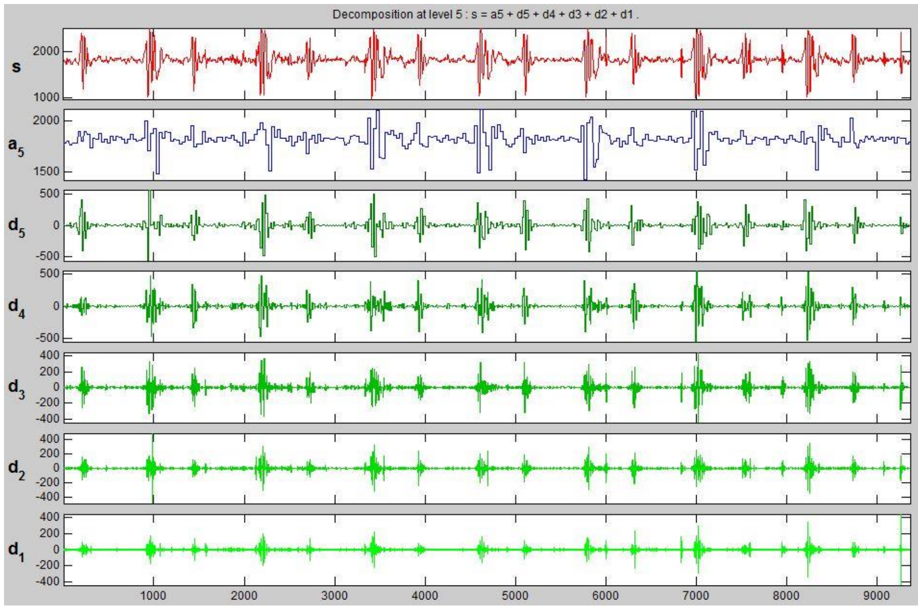

Figure 12. The results of wavelet transform performed on our signal

Waveforms from analog and digital part allow to manually extract the first and the second heart sound. Signal also contain a noise, so in the future de-noising procedure should be made. To automatic detection of events wavelet transform seems to be useful. The results of reconstructions the data after decomposition show, that particularly components can be used to further processing to determine heart sounds and intervals between each of them.

5. CONCLUSIONS

Digital stethoscope system can be designed in many different ways, but main elements are the same in many cases. In the selection of the sensor its sensitivity and quality of output signal is important. In our solution both bandpass and bandstop filters were implemented. The researchers, who focused on signal processing usually did not built their own detection system, but used commercially available electronic stethoscopes.

Signal processing applied to de-noise, extract features and make classification between normal and abnormal was implemented mainly using MATLAB® software. Wavelet transform was used to prepare best signal segmentation and neural network or HMM to signal classification [1,2,4,8,13].

We obtained promising results in both analog and digital circuit. In the future we plan implemented some methods to improve signal-to-noise ratio using digital filters and signal processing, in order to obtain automatic segmentation.

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