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ABSTRACT OF PHD THESIS

Research and implementation of medical electronic equipment, to use in cardiology

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Chapter 1. Introduction

The thesis is divided into five chapters, references and 20 appendices.

The contributions to numerical analysis of the PCG signal (PhonoCardioGraphs), this thesis aims to contribute to solving problems or improving the diagnosis of heart pathologies. So the thesis addresses the complex issue of development support and development of mathematical algorithms required for classifying cardiac pathologies using PCG signal. Also made contributions, thesis has the objective of substantially fills a gap in the way of characterization of a PCG signal. The marketing of prevention in cardiology equipment has grown due to increasing computing power at the portable device. The introduction of high-speed microcontroller with integrated DSP module makes possible to carry these devices with increasingly smaller dimensions.

Endpoints of the thesis are:

1. Development of the first algorithms applicable in a portable computer system for the characterization of PCG signals.
2. Research, design and realization of a prototype electronic equipment for complex analysis of the PCG signals.

Thus defined objectives give a practical research that has come following intermediate steps:

1. Developing the mathematical support for PCG signal analysis;
2. Design and testing of an algorithm for time-frequency scalogram representation;
3. Designing and testing a multi-resolution algorithm for entropy analysis of PCG signal;
4. Design and testing of a shape recognition algorithm for evaluating the signal envelope to classify cardiac pathology;
5. Inserting a pattern recognition algorithm used in 2D images based on Fourier transform convolution matrix of image content;
6. Software algorithm by numerical signal processing tools (DSP);
7. Design and realization of an operating system software for medical equipment with color graphics display capability;
8. Design and practical implementation of a prototype hardware system for medical equipment, capable to perform complex analysis of PCG signals.

Conclusions Chapter 1:

There were presented a number of pathologies as introductory module to detectable PCG pathology signals, the differences between sound accompanied by cardiac activity and cardiac murmur. There are presented the cases that lead to murmur, and may be associated with a certain type of heart disease or pathology class. Analysis of existing equipment by means phonocardiography investigation led to the idea to investigate and make a series of algorithms by which to detect cardiac pathologies and then they are implemented in a portable system. Thus were established general criteria under which it was possible to undertake research. The PCG signal analysis system had to be under autonomic computing capacity to determine the type or class of pathology at least detected. Using ten PCG signals with different pathologies were sufficient to begin research in this area.
Chapter 2. Medical signal processing using modern mathematical methods

Wavelet functions are used to convert the signal to be analyzed in a representation intended to highlight some features much better original signal. This transformation of the signal is called wavelet transform, which strictly mathematical point of view function is a convolution of the signal wavelet analysis. In signal analysis, wavelet transform can meet two possible roles: it can be translated along the signal may suffer compression or extension by rescaling respectively.

The wavelet functions are localized both in frequency and in time by shifting and scaling function without a projection over the entire transformed. Another important aspect is that in terms of number of calculations necessary for the Fourier transform is required when performing mathematical $O(n \cdot \log_2(n))$ operations on wavelet transform by fast algorithms can be reduced to $O(n)$ operations.

Each iteration of the decomposition of the signal is called octave that can assimilate a set of two FIR filter type. A wavelet transform filter is built-pass type (TJ) and the other is type-pass (TS). By direct application of wavelet transformed on a discrete signal, we obtain a double number of points for the half vector transform. Because the number of samples after every iteration transforms is equal to the number of samples of the original signal, it was proceeded to a decimation of two. Scaling behavior sequence is a sequence of wavelet pass filter and a filter is going up where both filters are normalized to have sum equal to 2. In some applications, sequences are normalized to have equal amount $\sqrt{2}$ remains orthogonal to each other.

Since in this case a number of coefficients will exceed the end samples, there will be remaining at the end of the return signal coefficients at the beginning to avoid the phenomenon of distortion to the limit. It can you build a reconstruction algorithm particularly useful for analysis of perfect reconstruction filters. Thus:

$$x_{m-1}(t) = \sum_n S_{m,n} \Phi_{m,n}(t) + \sum_n T_{m,n} \psi_{m,n}(t)$$  \hspace{1cm} (2.1)

Yields:

$$x_{m-1}(t) = \sum_n S_{m,n} \frac{1}{\sqrt{2}} \sum_k c_k \Phi_{m-1,2n+k}(t) + \sum_n T_{m,n} \frac{1}{\sqrt{2}} b_k \Phi_{m-1,2n+k}(t)$$  \hspace{1cm} (2.2)

After rearranging the terms of equation 2.2:

$$S_{m-1,n} = \frac{1}{\sqrt{2}} \sum_k c_{n-2k} S_{m,k} + \frac{1}{\sqrt{2}} \sum_k b_{n-2k} T_{m,k}$$  \hspace{1cm} (2.3)

The family of Daubechies functions plays an important role in signal analysis because it is most often used to break down into component sub-band signals. Using wavelet db4 requires calculating scaling coefficients. Coefficients are calculated using equation 2.3, the scaling equation for a function with four wavelet coefficients is written:

$$\Phi(t) = c_0 \Phi(2t) + c_1 \Phi(2t - 1) + c_2 \Phi(2t - 2) + c_3 \Phi(2t - 3)$$  \hspace{1cm} (2.4)

And the wavelet function with the corresponding equation results:

$$\psi(t) = c_0 \psi(2t) - c_1 \psi(2t - 1) + c_2 \psi(2t - 2) - c_3 \psi(2t - 3)$$  \hspace{1cm} (2.5)
Conclusions Chapter 2:

A summary was presented of how the mathematical need for research in digital signal processing PCG. From the analysis of this type of signal a need to use wavelet transform as the only effective way to achieve the desired results. Using wavelet transform as a starting point in analyzing a signal having characteristics very difficult to put into evidence led to the need to go through a complex mathematics which was only recently published. To deepen this material, the PhD student had to make a selection of mathematical methods for implementing best practice developed in computer algorithms. Building a well-structured mathematical device led to the selection and testing of the optimal wavelet function presented in the thesis.

Since the wavelet transform algorithms underlying design experience, to complete properly the mathematical apparatus was required mathematical theory covering elements, in parallel with the design and testing of the dedicated algorithms. Wavelet transform algorithms using time domain were developed based on signal filtration theory. This was done to allow the convolution algorithm for the DSP hardware.

Chapter 3. PCG signal characterization algorithms

The extremely complex structure of the PCG signal by analogy with an information carrier signal, is characterized by a low frequency amplitude modulated signal, followed by a frequency modulation "carrier" generated by the cardiac activity at different times in relation to the movement of valves, and finally the phase modulation signal is added to all components. The most important parameter is the frequency of PCG signal that is in the range 62Hz - 800Hz. In this chapter the original algorithms that allow analysis and characterization of PCG signals in terms of spectral, temporal components and layout of the signal envelope are specific to the cardiac pathologies. So the presentation of analysis algorithms through the following steps:

- Determination of the spectral wavelet packets;
- Wavelet decomposition analysis by evaluating the partial Shannon entropy;
- Accurate heart rate detection for signals with pathology;
- PCG signal multirate sampling;
- Detection of signal envelope;
- Conversion of two-dimensional correlation of PCG signals.

After calculating the entropy of wavelet transform coefficients, it can be defined the set of reference vectors to determine the Euclidean distance between analyzed signal and each reference signal. In mathematical form, a reference signal becomes the Shannon entropy values in a matrix, which includes approximation coefficients and those of detail. So the entropy of each level of decomposition will replace the matrix lines. This method drastically reduces the amount of memory used to store reference signal associated with cardiac pathology. The simulations done to characterize the PCG signals by calculating Shannon entropy, were made on a number of 10 signals belonging to different pathologies including some different classes.

The simplest algorithm used in pattern recognition is the Euclidean distance calculation. A set of predetermined reference arrays is computed by calculating the Euclidean distance between each of the matrices and matrix pathology reference signal acquired. The method of calculating the Euclidean distance between two matrices is given in equation 3.1:
\( d(p_j, q_j) = \sqrt{\sum_{j=1}^{m} \sum_{j=1}^{n} (q_{ij} - p_{ij})^2} \)  

(3.1)

There is the final form of the PCG signal correlation algorithm, including the algorithms developed in previous subsections 3.4, 3.5 respectively 3.6. Thus accurate determination of heart rate is presented in section 3.4 in order to determine the relationship between heart rate signal to be analyzed and the reference signal. The value of ratio between the two signals will indicate the re-sampling factor used for translation in time of PCG signal given in section 3.5. The correlation algorithm is shown in Figure 3.11.

![Figure 3.11 The correlation algorithm](image)

Conclusions Chapter 3:

It was presented a set of algorithms for processing digital signal PCG, who are part of the three methods of pathologic classification. The first method involved the analysis of spectral content of the PCG signal and then based on a complex algorithm; frequency spectrum is displayed on a color LCD display. This method of evaluating a signal is addressed to medical personnel who can interpret the created time-frequency scalogram. The second method involves analysis of statistically calculating the signal so that the Shannon entropy of wavelet decomposition on each level, showing a specific value for each pathology in part. This density acts as an information fingerprint of the signal which allows automatic pathology classification of the detected PCG signal. The third method is the most complex driven by the large number of algorithms, so that the correlation signal is acquired with a series of reference signals stored in the SD memory system created for this purpose. PCG signal correlation method includes an algorithm accurate heart rate detection using autocorrelation function. Determining the precise heart rate is dictated by the needs of rescaling temporal wavelet decomposition level of three to bring the acquired signal to the same HBR value of the reference signal. Last step is to precisely detect the signal envelope PCG Hilbert transform using a discrete signal. The correlation signal is prepared by converting the signal into a two-dimensional vector, making the actual signal in a two-dimensional image. This method opened the way to the methods of imaging especially for shape recognition.

The sum of these presented numerical processing methods is an important step in the processing of a signal virtually unapproachable by traditional methods of numerical processing.
Cap.4 Research, design and implementation of electronic medical equipment

The functional diagram of the device is divided into two modules. This module identifies (north side) in which is the DSP microcontroller and the (south-master) module which manages the flow of data within the device. Each module is composed by a Microchip microcontroller series. Block diagram of the device is shown in Figure 4.3.

![Block diagram of the PCG signal analyzer](image)

Figure 4.3 Block diagram of the PCG signal analyzer

The electrical diagram has been designed using the CAD capabilities of the Labcenter-Proteus program, in which we generated the necessary missing components, from libraries. After exporting the net list files we have moved to the PCB design. Complete wiring diagram is shown in Appendix 1. Due to the large number of data ports used in the scheme was necessary to define rules for tracking and generating the list under semi automatic routing procedure. The total duration of CAD computing was 18 minutes without including the duration of checking of the arranged paths correctness started in manual mode. The printed circuit boards are presented in Appendix 3 and 4. The wiring design is completed by a set of Gerber files exported in RS274X format. The two PCB circuits were assembled in a professional way by using HAL (Hot Air Leveling), finish double layer, non-Pb solder mask by the company AR-Elektronik in Germany. All SMD components were soldered manually. The 3D simulations can be seen in Appendix 2 and the final realization of both sides of the printed circuit board having all the components, placed can be seen in Figure 4.5:
In Figure 4.30 we can see the medical device in operation.

Figure 4.5 The PCB board of the electronic device

Figure 4.6 The PCG signal analyser

DSP module is the basic component of the microcontroller dsPIC30F6012 and is specialized in the execution of fast instructions such as addition, subtraction and multiplication. The next equation is fundamental in digital signal processing and as a mathematical point of view it is based on the convolution operation. The development is designed so that it carries out all signal analysis processes using equation 4.1:

$$S = \sum_{i=0}^{N-1} a_i b_i$$  \hspace{1cm} (4.1)

Recursive FIR filter implementation can be done easily by using modulo addressing type programming which provides after beginning of the routine the return of the address used to the filter coefficients. Hilbert transform calculation assumes a similar algorithm but to simplify the modulo addressing type, due to the reduced number of Hilbert coefficients by inserting in the loop list the necessary zero values. The integrated analog-digital converter circuit is a 12-bit SAR structure. Conversion speed can reach up to 500Khz. The developed prototype uses a sampling rate of 8KHz, otherwise low frequency resolution which is a audio standard. The National Instruments LabWindows CVI platform uses a set of communications protocols implemented with NI-VISA. This protocol is a
set of application programming interfaces for high-level (API) in order to provide communication interfaces to a PC with various tools attached. The USB protocol allows that the applications written, to transfer the SD reference signals, the programming of the graphical elements used by the device, the direct reading of RAM and also the reading of the final results following the assessment of PCG signal. The communication is specific to this device and was created exclusively for this application to access the SD memory through a USB protocol.

**Conclusions C4:**

It was presented an electronic device for signal acquisition and numerical processing of the PCG signals. It was researched, designed and made practical by using modern electronic design. There were presented the two major components of this device structure, which includes operating system software created for this purpose. The hardware structure comprises a color graphic LCD display that can display a graphical user-friendly menu driven by a set of three keys to access the operating system. Data storage is done by using an SD memory card, which has the advantage of virtually unlimited memory space relative to the size of generated files. These files are generated from blocks with a total size of 64KB each. A communication protocol was developed a high speed USB device designed thereby serving the exchange of information with the host program resident on a PC. The operating system is autonomous in operation but during the test routines are emulated by transferring computer data to microcontroller DSP.

The thesis is within the field of digital signal processing and was completed by the design and realization of a DSP system development capability. This development system was designed for the acquisition and analysis of PCG signal and end with the characterization and recognition of cardiac pathologies. So the whole thesis contains the theoretical apparatus necessary for the design, calculation and completion of practical algorithms for this type of signal analysis.

Initial processing of the signal was made by wavelet transform to perform spectral decomposition PCG signal while carrying out data compression to reduce the number of calculations in the DSP processing. The characterization of the PCG signal that has a very complex structure was achieved through the implementation of three methods. Thus the first method provides a time-frequency representation through a PCG signal scalogram. Thus PCG signal is converted into a graphical form more easily interpreted by your cardiologist. A second method of characterization of PCG signal is by calculating the statistical type of information density wavelet decomposition levels. The Shannon entropy calculation method uses the signal sequence results after wavelet decomposition of the PCG signal. The third method used to characterize the signal is by the conversion based on the signal obtained in a two-dimensional vector form. Thus PCG signal is processed as a 2D image. The resulting images were decomposed into a reference signal with a specially written program. The references signal results were also used in the matching algorithms in images processing.

**Cap.5 Original contributions**

The resulting algorithms were tested by simulation programs designed in C language using LabWindows CVI National Instruments environment. After the simulations, it was switched to recompile the programs for the microcontroller implementation. The final DSP routines will be made after on board emulation of the computer algorithms. The personal contributions are indicated as referred to the full version of the thesis:

- Own method for wavelet decimation filtering algorithm implemented in language C, on the basis of multi-resolution theoretical wavelet transform (section 2.10)
• Own method for determining the wavelet function by calculating the reconstruction error, suitable for performing signal decomposition PCG (section 2.11, Table 2.1, Table 2.2, Figure 2.14, Figure 2.15.)

• Own and original method to implement time-frequency scalogram on an embedded micro system using color graphic display features (section 3.2, Figure 3.8, Figure 3.11). Summary of results is shown in Figure 5.1.

• Designing GUI building program for displaying time-frequency scalogram (Appendix 12).

• Own statistical evaluation method by calculating multi-resolution decomposition of the Shannon entropy partial application of Euclidean distance. (Section 3.3 Table 3.1, Table 3.2, Figure 3.14, Figure 3.15) Summary of results is shown in Figure 5.2.

• Own method for determining precise heart rate in a pathological conditions with noise signals, by autocorrelation of the level three wavelet decomposition (section 3.4, Figure 3.18)

• Untreated original method in other literature, the translation time of PCG signals multirate fractional sampling. This method preserves all the original features of the signal amplitude. Summary of results is shown in Figure 5.3.

• Untreated original method in other literature to determine the envelope of the PCG signal using Hilbert transforms. Summary of results is shown in Figure 5.4.

• Untreated original method in other literature, the PCG signal correlation methods as digital imaging. Summary of results is shown in Figure 5.6.

• Design of a multifunction development system having PCG signal processing capabilities by using DSP module (section 4.2.3, Figure 4.29)

• Design of a software interface for programming graphical color LCD display DEM128160 (section 4.1.4, Figure 4.7, Figure 4.11, Figure 4.12)

• Designing the program needed to convert RGB565 LCD display (Appendix 13)

• Support program for calculating FIR filters coefficients for the Q1.15: calculating bandpass input filter and FIR filters for calculating the multirate sampling (Appendix 11)

• Designing a multipurpose program for communication between the host program installed in a PC and the electronic equipment (Appendix 12)

• Development and implementation of a communication protocol for devices designed by using USB2 interface in the Medical Engineering department (Appendix 15)

• Performing various circuits based on microcontrollers for use by students of the Medical Engineering Department.

• Promote the idea of analysis device display features local PCG signals

• Writing of 6 scientific articles published on the PCG signal analysis, ECG, and portable devices equipped with complex data analysis capabilities.