Measurement and Analysis Possibilities of Pulse Wave Signals

Stefan BORIK, Ivo CAP

Department of Electromagnetic and Biomedical Engineering, Faculty of Electrical Engineering, University of Zilina, Univerzitna 1, 010 01 Zilina, Slovak Republic

stefan.borik@fel.uniza.sk, ivo.cap@fel.uniza.sk

Abstract. *This article deals with the implementation of wireless data transfer in biomedical applications concretely in photoplethysmography and pressure wave measurements. It deals with the application of a Bluetooth module for data transfer to the computer where further signal processing can be performed. The work describes a use of microcontroller serving for data flow control, communication and analog signal digitalization.*

Keywords

Bluetooth, microcontroller photoplethysmography, pulse wave, sensors.

1. Introduction

This article deals with design and realization of photoplethysmographic device serving for pulse wave investigation based on principle reflective photoplethysmography and with design of device prototype serving for pressure pulse wave measurements. The work describes sensor and hardware design, functionality principle, digitalization and data transfer using a Bluetooth module. A part of work involves analog signal processing such as signal amplification, filtering. The article is focused on data transfer to PC using selected microcontroller with integrated A/D converter and on the application of Bluetooth module serving for wireless data transfer.

2. Photoplethysmographic Device Design

2.1. Photoplethysmography

Suitable detection method for pulse wave investigation is photoplethysmography which serves as a diagnostic method for detection of blood volume changes in a selected part of the vessel or skin. It can serve with ECG measurements as useful diagnostic method for estimation of the cardiovascular system state. Basic principle is based on infrared radiation application to cutaneous area and on its reflection depending on blood volume changes. Reflected radiation corresponds to the propagation of pulse wave [1], [2], [3], [4], [5].

2.2. Sensor Design

Photoelectric detectors can be used for measurement. They detect either passing (transmission through tissue) or reflecting wave (reflection from tissue). Recorded pulse wave (see Fig. 3.) is similar to pressure wave curve [2].

Sensor was created from phototransistor and IR (infrared) diode (Fig. 1). Working wave length of this couple is 940 nm. Sensor is based on principle of radiation reflection.

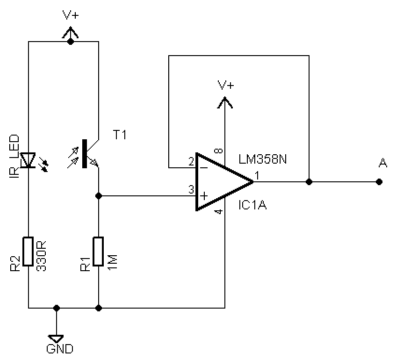

Fig. 1: Sensor circuit.

The used operational amplifier LM358 (shown on Fig. 1) serves as a voltage follower for an impedance matching. The signal from the voltage follower inputs to the first stage of two operational amplifiers serving for signal amplification because the signal from sensor output is small and it is needed to be amplified for further processing. A gain of the amplifier (Fig. 2) is set by resistors R_3 and R_4. It can be calculated by the next equation:

$$G = \frac{R_4}{R_3} = -100. \tag{1}$$

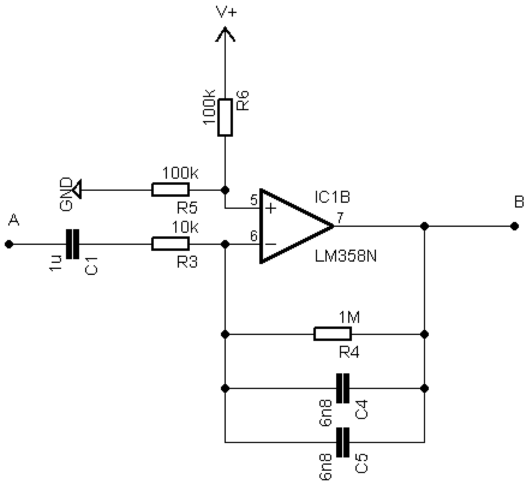

Fig. 2: First amplifier stage.

The capacitor C_1 and the resistor R_3 represent high pass filter with cutoff frequency f_{ch}:

$$f_{ch} = \frac{1}{2\pi R_3 C_1}. \tag{2}$$

The capacitors C_4, C_5 and the resistor R_4 represent low pass filter for filtering noise such as mains noise:

$$f_{cl} = \frac{1}{2\pi R_4 (C_4 + C_5)}. \tag{3}$$

Second amplifier stage has the same function as the first stage.

Both amplifiers have a single power supply. For that reason it is needed to create a virtual reference voltage on their non-inverting inputs. A half of power supply ensures that the signal amplitude swings around this value (+1,5 V). It is between supply voltage (+3 V) and ground [2], [6].

3. Microcontroller Based Signal Processing

The analog output signal is needed to be digitalized. For that reason integrated analog to digital converter (ADC) which is part of a selected microcontroller ATmega88A was used.

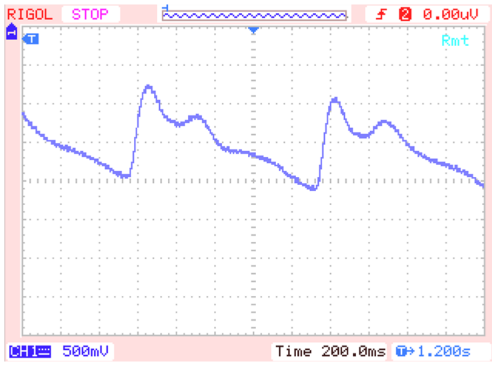

Fig. 3: Output signal measured by oscilloscope.

3.1. ADC Settings

The microcontroller ATmega88A offers the analog to digital converter with 10-bit resolution. A sampling frequency of the converter depends on a frequency of the connected crystal. In our case its value is 18,432 MHz. Regarding to the datasheet of manufacturer it is recommended to set the converter input frequency to range from 50 kHz to 200 kHz. In this way correct function of the converter is ensured. Dividing of the input frequency is done by setting of prescaler bits shown in the next table.

Tab. 1: ADC prescaler selections.

ADPS2	ADPS1	ADPS1	Division factor
0	0	0	2
0	0	1	2
0	1	0	4
0	1	1	8
1	0	0	16
1	0	1	32
1	1	0	64
1	1	1	128

By selecting of the division factor to 128 the input frequency is set to 144 kHz and it corresponds to the recommended value.

3.2. Conversion

After enabling of ADC (ADEN bit is set to the logical one) the function for conversion can be periodically called in a main loop of the program. In this function following parameters are set:

- Input channel selection (bits ADMUX),
- ADC left adjust result (bit ADLAR to 1).

By setting the bits MUX0 and MUX2 channel 5 is selected and 8-bit conversion result is selected by setting ADLAR bit to the logical one. The 8-bit resolution of the conversion was selected for higher transfer rate achievement using RS232 protocol. It follows that by using 3 V power supply the voltage resolution (VR) is about:

$$VR = \frac{3}{2^8 - 1} \cong 12 \; mV. \tag{4}$$

The conversion starts after setting these control bits. In a loop bit ADIF is compared to logical one. If its value changes from zero to one the conversion is complete and the conversion result can be read from the 8-bit register ADCH. Its value can be calculated by the following equation:

$$ADCH = \frac{V_{IN}}{V_{REF}} \times 2^8, \tag{5}$$

where V_{IN} is an analog input voltage and V_{REF} is internal voltage reference 3 V.

3.3. Serial Communication

Digitalized data are sent using UART (Universal Asynchronous Receiver Transmitter) unit which is compatible with RS232 protocol. For correct function of this unit appropriate setting of baud rate generator is needed. Correct setting of UART baud rate generator register value allows baud rate generation without errors. For that reason the external crystal with the frequency 18,432 MHz was selected. The parameters of serial data transfer are shown in the next table:

Tab. 2: Parameters of the serial link.

Parameter	Value
Baud Rate	57600 B
Stop Bits	2
Parity	Even

3.4. Microcontroller Circuit Design

The used microcontroller ATmega88A requires for its function power supply voltage between 1,8 and 5,5 V. As the power supply a mobile phone battery was selected because the designed device should be serving for permanent patient monitoring and shouldn't limit his/her free movement with power supply cables. The battery output voltage is 3 V. The microcontroller circuit diagram is shown on the next figure:

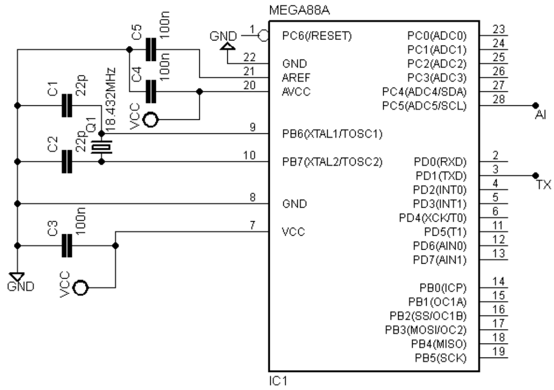

Fig. 4: Microcontroller circuit.

4. Investigation of Pressure Wave Propagation

There are two phenomena which are connected with a heart activity. By stroking function of heart the blood is ejected to circulation in a form of flow pulse wave propagation. The second phenomenon is distension of arteries propagating through whole systemic circulation. In this way a pressure pulse wave propagates to periphery and the arteries represent a medium for this propagation. Its velocity depends on many factors e.g. compliance, elasticity, diameter, thickness of arteries and intravascular pressure [1], [5], [6]. These parameters change with age. The velocities in the young subjects are shown in the next table [1]

Tab. 3: Pulse wave velocities.

Arterial type	Velocity $[\mathrm{m \cdot s^{-1}}]$
Aorta	3–5
Large arteries	7–10
Small arteries	15–35

The pressure wave can be measured by various methods. A measurement principle is based on use appropriate converter which converts mechanical energy to electrical energy. As converter piezoelectric transducer or pressure sensor can be used.

4.1. Device Prototype for Pressure Wave Measurement

For conversion of mechanical energy to electrical energy the pressure sensor SPD015G was selected. This sensor consists of four silicon resistors which are connected in bridge.

These resistors are in a plastic package which has two mechanical openings. The one serves for selected pressure measurement and the other is for reference.

A cuff is connected to the measurement input by rubber hose. This cuff is placed for example on the arm of subject and by using of pump the air is pumped to it. In this way the cuff can encircle arteria brachialis which runs through this place. Sensor, cuff and pump are in the next picture:

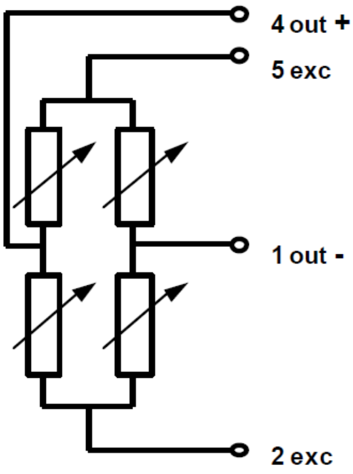

Fig. 5: Internal pressure sensor circuit (adapted from manufacturers datasheet).

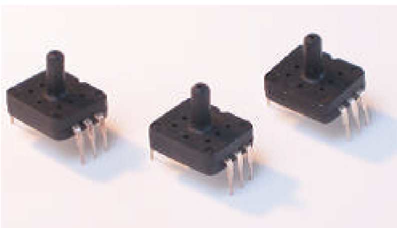

Fig. 6: Sensor package (adapted from manufacturers datasheet).

Fig. 7: Sensor, cuff and pump.

4.2. Electrical Circuit

Sensor output voltage corresponds to pressure wave propagation. Signal from the sensor has to be amplified. Primary amplification was realized by instrumentation amplifier INA 122 which serves for low-noise differential amplification of the signal. Manufacturer describes this amplifier that it provides excellent performance with very low quiescent current and is ideal for portable instrumentation and data acquisition systems. The INA122 can be operated with a single power supplies from 2,2 V to 36 V and quiescent current is a mere 60 mA. A single external resistor sets the gain from 5 to 10000.

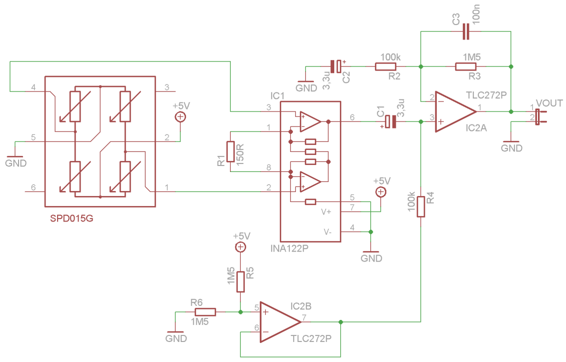

Fig. 8: Electrical circuit.

For filtering of the output signal operational amplifier TLC272 was used. The capacitor C_3 and resistor R_3 represent low-pass filter. This amplifier serves also for amplification of the signal. Selection of a single element values depends on the need of signal details.

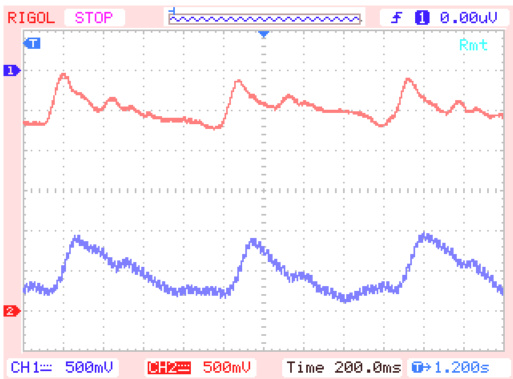

Fig. 9: Pressure wave measured by oscilloscope.

5. Wireless Data Transfer

For wireless data transfer Bluetooth® communication protocol was selected. From many devices module BTM-112 from Rayson was selected due to its performance ratio.

5.1. Bluetooth Module BTM-112

The selected module allows measured data transfer using serial communication protocol. For that reason another module is needed for the creation of a virtual serial port in the computer, which serves for further signal processing. It can be achieved by using conventional Bluetooth serial link adapter available on the market. The BTM-112 module has the following features:

- Bluetooth standard Ver. 2.0,
- Internal 1,8 V regulator,
- Low current consumption : average 46 mA,
- 3,0 V to 3,6 V operation,
- Support for up to seven slaves,
- Interface: USB, UART, PCM,
- SPP firmware with AT command sets,
- Small outline: 25 x 14.5 x 2.2 mm.

Fig. 10: BTM-112 module.

5.2. BTM-112 Settings

The settings of the selected module can be changed by using appropriate AT commands. All the AT commands except the "AT" test command use the below command structure:

¡header¿¡name¿¡ parameters¿ ¡cr¿

The module is shipped with the following default factory setting of UART:

- Baud rate: 19200 B,
- Data bits: 8,

Tab. 4: AT commands.

header	Each command will start with "AT" character sequence.
name	Command name.
parameters	The parameters are required for most of the commands. The parameter may be character, integer and character sequence (BD address, Pin code, Name, etc.) depending on the command operation.
cr	This character terminates the command packet and signals the device to proceed with command execution.

- Parity: none,
- Stop bits: 1,
- Flow control: H/W or none.

For that reason it is needed to change the parameters of the transfer. For our purposes we used the commands shown in the next table:

Tab. 5: Used AT commands.

Command	Name	Parameter
ATL	Baud Rate	4
ATK	Stop Bits	1
ATM	Parity	2

By using these commands desired serial link settings were achieved as it was described in Tab. 2 [7], [8].

5.3. Function Principle of BTM-112

If the conversion of the analog signal is done, microcontroller sends data to the RX pin of the module and the data are automatically sent to the PC by this module. The circuit diagram is shown in the Fig. 11.

6. Measured Data Analysis

Within this work we performed measurements on selected subjects and we tried to increase measured data worth by application of specific algorithms. There are many approaches to evaluate measured PPG curves. We can introduce comprehensive background research work of [9]. In this work we can read that it is possible to evaluate PPG signal curves in many ways. For our

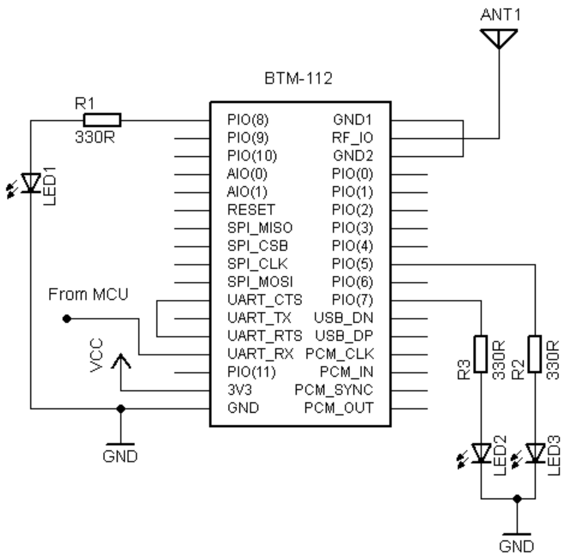

Fig. 11: BTM-112 – circuit diagram.

contribution we selected the second derivative of photoplethysmogram (SDPG) and we created the application for investigation SDPG curves parameters which are interconnected with state of the cardiovascular system parameter such as e.g. vascular compliance or elastic modulus [10], [11], [12], [13], [14].

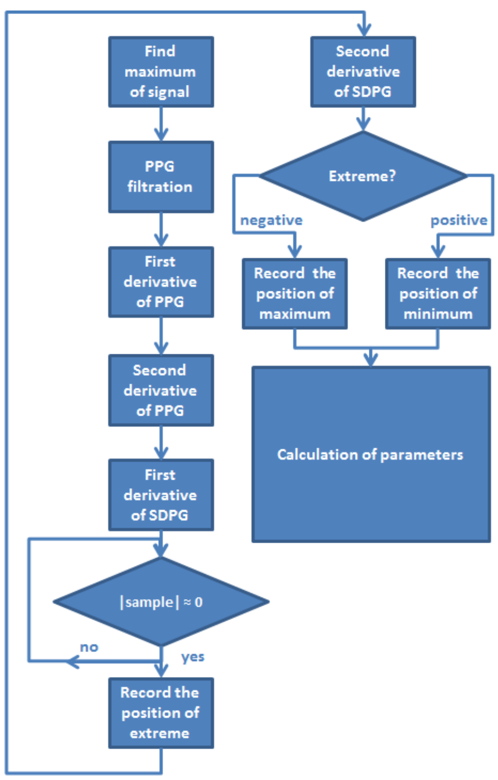

Fig. 12: Data analysis algorithm.

6.1. GUI for Evaluation of SDPG

An application for evaluation of SDPG was created in MATLAB programming environment. It is possible to evaluate measured PPG curves in this application and information about arterial elastic modulus can be obtained.

At first measured PPG curve has to be filtered because the next operation is a derivation of PPG signal. Without digital filtering of measured data noise is amplified by deriving of given signal. For data preprocessing was used moving average filter. Afterwards we applied first and second derivation to filtered signal and by that way we obtain SDPG curve. At this step it is needed to detect local maxima and minima of SDPG signal. If the absolute value of compared sample is around the zero then the position of local extreme is recorded. Afterwards the recorded local extremes are investigated. If the current recorded extreme has positive value then the position of local minimum is recorded and if the local extreme value is negative then the local maximum is detected. The data processing algorithm is shown in the Fig. 12.

Realized GUI for PPG analysis is shown in the Fig. 13. By using this application user can evaluate and determine the SDPG parameters such as peaks a, b, c, d and e. After determining of these peaks the single ratios are calculated which are interconnected with state of the cardiovascular system concretely with elastic modulus of arteries [10], [11], [12], [13], [14].

Measured b/a ratios are comparable to data presented by [10]. Our calculated slope of the trend line was 0,008 (see Fig. 14). This result is equal to result of the work [10].

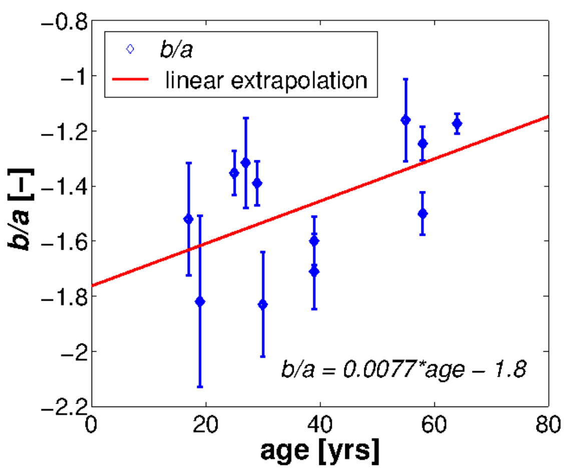

Fig. 14: Measurement results – b/a ratio dependence on age of measured subjects.

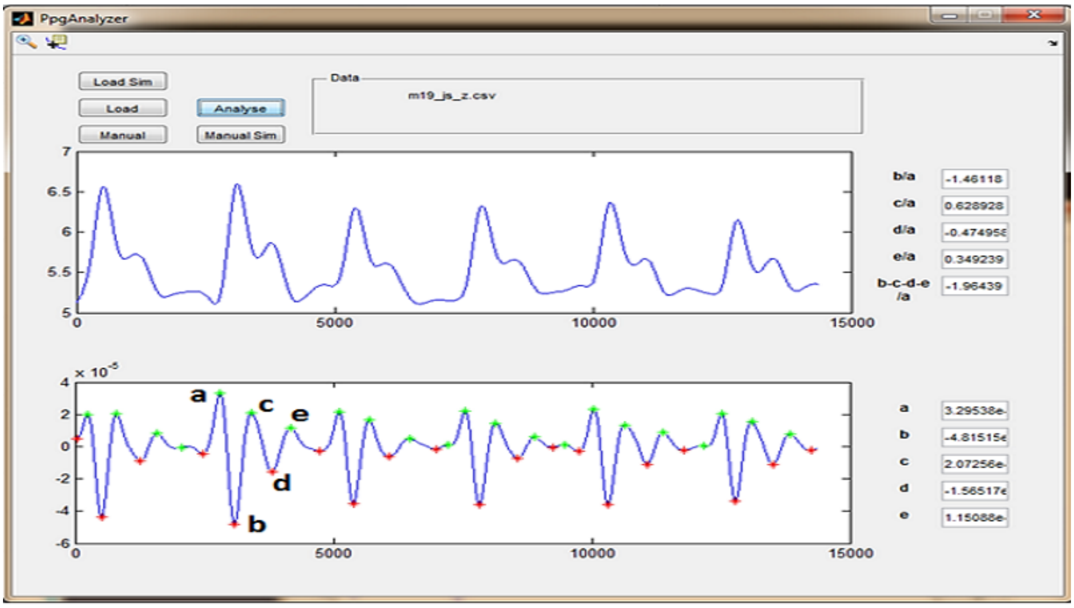

Fig. 13: Graphic user interface for PPG curve analysis.

7. Conclusion

Within the work device for scanning of the flow and pressure pulse wave was designed. Both types of pulse waves measured by these two principles can be compared and the comparison results could help to understand properties of the arterial system.The devices have two parts: analog and digital. The analog part serves for the analog signal amplification and filtering. The digital part is based on the use of the microcontroller which allows signal digitalization using integrated analog to digital converter. The microcontroller serves also for controlling of wireless data transfer. For this type of data transfer Bluetooth module was selected because standard mobile devices dispose of Bluetooth communication interface. The designed device should serve for patient monitoring and allows free patient movement without restrictions caused by communication and power supply cables. The patient can be monitored by a doctor for example by sending a message from his mobile phone. Within the work further analysis of measured and transferred data was presented. We created graphic user interface serving for PPG curve evaluation by using its second derivative SDPG. Calculated b/a ratios are interconnected with elastic modulus of arteries and they can give us information about vascular aging of measured subject. Measurement results could be combined for example with the existing model of the cardiovascular system based on electromechanical analogy. In this way the elastic modulus of arteries could be determined by comparing of measured and simulated data.

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About Authors

Stefan BORIK was born in 1986. He received his M.Sc. from Faculty of Electrical Engineering, Department of Electromagnetic and Biomedical Engineering, University of Zilina in 2011. In the present time he is a Ph.D. student at the University of Zilina. He especially deals with analog and digital hardware design, biological signal processing and modeling.

Ivo CAP was born in 1948. He graduated from the Czech Technical University in Prague, Faculty of Electrical Engineering, CSc. (eq received at the Slovak Academy of Sciences, Institute of Electrical Engineering, professor of Physics of condensed matter and Acoustics at the University in Zilina. The present appointment is professor of Biomedical Engineering at the Faculty of Electrical Engineering of the University of Zilina. He is specialized in modelling of physiological processes, influence of EM field on living organisms and EM non-destructive testing of conducting materials.