Full Length Research Paper

Wireless electrocardiography system

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Design and realization of a wireless PC-based system for electrocardiography and data acquisition of a patient's heart condition is described in this paper. The system is designed and realized according to virtual instrumentation concept consisting of two subsystems: 1) The battery powered external compact and mobile wireless ECG acquisition hardware on the side of patient and USB connected communication wireless module on the PC side; 2) Standard personal computer with graphical user interface and database support. The USB port is selected to be the communication interface between the ECG acquisition hardware and the PC and also to supply power to the communication wireless module at the PC side. The Graphical User Interface (GUI) is designed in the traditional style of ECG paper plots and additional displays based on suggestions of cardiologists. Strict medical requirements are respected in the design of the system.

Key words: ECG, virtual instrument, wireless, MCU.

INTRODUCTION

Personal computers have become a standard platform for the needs of various measurements and tests, primarily due to its standardization, performance and low cost. With their performance, which is becoming ever higher, and with the increasing number of software applications, they are widely accepted as an essential tool on the desks of engineers. The use of PCs in so-called virtual or personal instrumentation development (Chiulan et al., 2008; Yao, 2008; Žorić et al., 2005) enables the realization of a new generation of superior devices. As the central role in the virtual instrumentation concept is played by the software (Sumathi et al., 2007; Žorić et al., 2004) the costs of development, maintenance and reconfiguration of instruments are reduced significantly. For example, increasing number of biomedical applications use virtual instrumentation to improve insights into the underlying nature of complex phenomena and reduce costs of medical equipment and procedures (Singh et al., 2008; Ekström, 2006).

Many software packages for virtual instrument development and realization are available now on the market. The software application, developed using dedicated or general purpose software packages, and appropriate additional hardware makes the virtual instrument (Garrett, 2002). In addition, many of the virtual instrumentation development tools, such as LabView (Sumathi et al., 2007), directly support integration of virtual instruments in the Internet environment (Ko et al., 2001). The Web technologies make possible creation of sophisticated client-server applications on various platforms, using interoperable technologies such as HTML, Java Applets, virtual reality modeling language, and multimedia support.

The selection of a communication interface between the acquisition hardware and PC depends on the requested transfer bit-rate and its cost. In most virtual instrumentation flexibility of use and costs are preferred in relation to maximum bit-rate. The new solution for the PC-based wireless mobile system for electrocardiography is proposed in this paper. It is designed according to virtual instrumentation concept and with respect to user requirements.

The measurement hardware which controls the

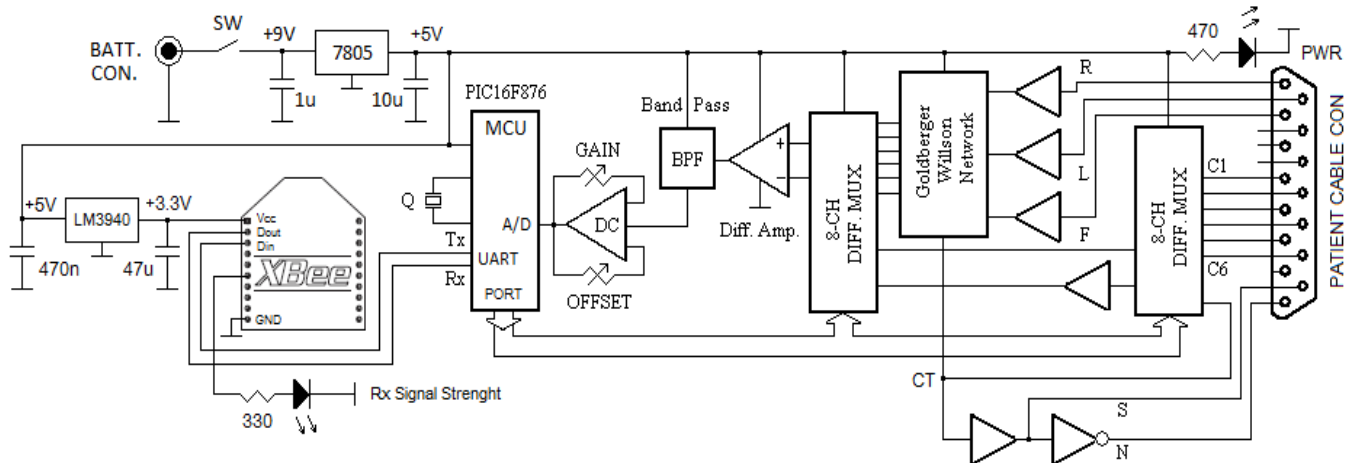*Corresponding author. E-mail: acazoric@yahoo.com. Tel: +381638649445.

Figure 1. Block diagram of stand-alone acquisition hardware of the wireless electrocardiograph.

acquisition part of the system, and the user software which controls remaining system parts such as analysis, data storage, report generation etc., are considered in this study. The software support is developed in Microsoft.NET Visual C++ according to the requirements of the cardiologist and virtual instrumentation concept.

The system is realized for medical needs of monitoring and recording 12 leads of the heart bio-potentials. It is a modern and low cost device to predict a patient's condition with mandatory help of a cardiologist.

Functional requirements

The proposed virtual electrocardiograph is based upon user requirements as suggested by cardiologists and respecting the virtual instrumentation concept in the study of Sumathi et al. (2007). The design of the system, with respect to the mentioned concept, assumes:

1. Initialization and optimal hardware control,
2. Development of algorithms and procedures for data processing,
3. Gui development for interaction between user and instrument.

In the development phase, the user requirements and adopted standards for traditional instrument should be respected along with the requirements mentioned earlier. Special considerations must be given to the detection of potential errors caused by inappropriate use of hardware or procedures. The main user requirements were the following functional and control system performances:

1. Selection of one of the twelve leads for real time monitoring and recording by the descriptive and intuitive GUI.

2. Recording of waveforms for each of the twelve leads during a time interval of six seconds. The software should enable recording of the ECG waveform 6 seconds prior to or after the command is issued.
3. Database connection.
4. Filtering of the public power network frequency.
5. Possibility to zoom the waveform.
6. Beep sound generation when R waveform of QRS complex appears.
7. Printed report generation (waveforms of 12 leads and cardiologist diagnosis).
8. Easily portable, battery powered module with patient cable on the side of patient that transmits sampled data wirelessly to USB connected wireless transceiver (plug into PC and use).
9. Possibility to calibrate the module.
10. 100 % patient's body insulation and negligible influence of inter-electrodes currents on heart bio-potentials.
11. Simple to use and on line user manual.

Hardware architecture

As mentioned earlier, the hardware of the system was divided into stand-alone wireless acquisition hardware on the patient side as shown in Figure 1, and USB communication wireless module at the PC side, Figure 3, both based on PIC MCU and × Bee RF modules. The battery powered acquisition hardware collects and processes signals from the patient cable electrodes and send them to the remote PC via × Bee RF module. There is the additional wireless communication hardware at the PC side connected with PC via USB port. This hardware is powered by USB power lines and communicates with acquisition hardware and PC's user interface. PIC MCU has been used for realization of both hardware parts.
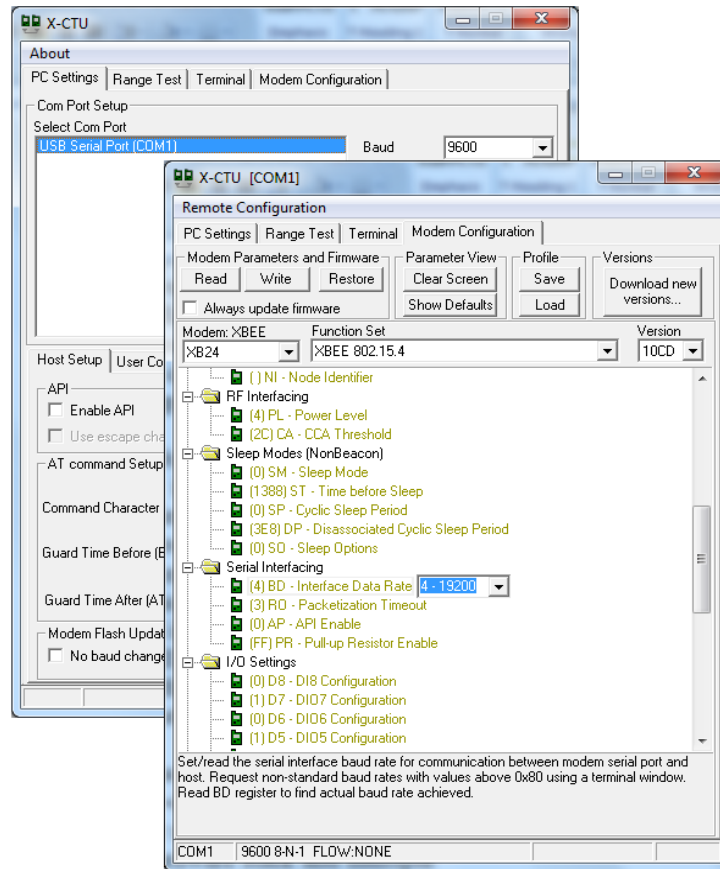
Figure 2. X-CTU configuration software.

The R, L, F, C1 to C6 (15-pin connector) electrodes are connected to the input of JFET impedance converters (four buffer amplifiers) which provide unity voltage gain with high-input impedance, see Figure 1. They serve to eliminate inter-electrodes currents owing to high-input impedance too. Because of this high impedance function, variations of patient-electrode resistance are less critical. The outputs of the buffers are connected to the Goldberger-Wilson resistive network. By connecting a resistance to each limb electrode and interconnecting the free wires the Wilson central terminal CT, which represents the average of the limb potentials, is formed (star configuration). Three additional augmented leads are formed by Goldberger triangular resistive network.

There is a signal from the resistor network which goes through the impedance converter and excites the shield of a patient cable (denoted by S in the Figure 1). Common-mode pickup on the patient's body is cancelled by the right-leg driver (denoted by N in the Figure 1). The right-leg driver feeding back to the patient a signal in 180° phase shifted to the common-mode pickup on the body.

The selection of one of twelve leads is executed by the microcontroller addressing the two 8-channel differential multiplexers. The selected signal is then amplified by the differential amplifier and filtered by passive band-pass RC filter (f_{Low} = 0.23Hz f_{High} = 56Hz). To calibrate the module, a gain and offset (base line) of the DC amplifier should be adjusted. The output of the DC amplifier is connected with one of five channels of 10-bit A/D converter of the microcontroller.

The XBee RF module (*MaxStream*) was utilized for wireless connection of the ECG acquisition hardware with remote PC. It allows the possibility of the real time process monitoring and recording on the distant location without cabling. As can be seen from Figure 1, communication between the PIC MCU and XBee RF module is established via USART periphery of the PIC MCU and serial data interface of the configured RF module. Operating voltage of the module is 3.3 V but digital inputs are 5 V tolerant. The modules operate within the ZigBee protocol (Dunbar, 2001) and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between remote devices within the ISM 2.4 GHz frequency band. RF modules have been easily configured by free X-CTU configuration software as shown in Figure 2, first as Coordinator and second as End device at the point-to-point topology. Both
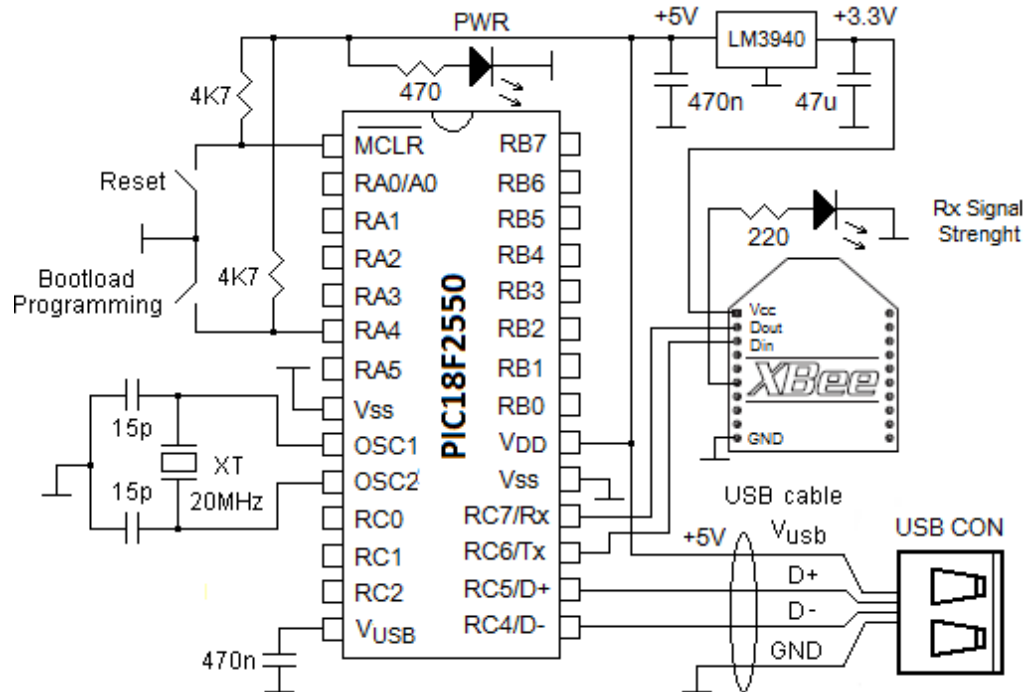
Figure 3. USB communication wireless ECG module at the PC side.

short 16-bits addresses have been matched as well as the baud rate. The RF module conforms to the 802.15.4 specification and supports both short 16-bit addresses and long 64-bit addresses. Each RF module is equipped with half-wave dipole antenna. Figure 3 shows simple serial communication between the RF module configured as End device and PC via USB port or precisely by emulating RS232 over USB.

The communication device class (CDC) specification defines many communication models including serial emulation. By using the relevant CDC built-in functions integrated in the MCU PIC18F2550 firmware and appropriate driver, virtual COM is created. This is necessary because the graphical user interface has been designed to be connected with serial COM port of the PC. Simultaneously, the power lines of the PC's USB port serve as power supply lines of the acquisition hardware due to large current capacity of 500 mA and stable voltage of 5 V. In this way, the communication module at the PC side becomes independent on the external power supply sources. Two buttons in the scheme serve for in-circuit serial programming of the microcontroller on the base of stand-alone USB bootloader program. So, the engineer can easily upgrade firmware, written using CCS C compiler, without need of disassembling the hardware and with CCS C compiler's serial monitor tool support.

Figure 4 shows the appearance of developed prototype of the ECG device. As can be seen, it consists of two parts: mobile wireless ECG acquisition hardware and USB based communication wireless module. The

firmware for PIC16F876 MCU is written using CCS C compiler IDE version 4.057 and loaded into the program memory of the MCU. The code is organized in several parts. The source code consists of two blocks, firstly for initialization and configuration of peripherals of the microcontroller, secondly for the USART interrupt handling which executes cyclically until an interrupt occurs. The transfer bit-rate of two byte result of A/D conversion is set to be 19200 Bauds with a sampling rate of 960 Hz. The interrupt routine is activated upon the receipt of a coded byte from the PC. The routine then selects the appropriate channel of multiplexer or stops the program execution, dependent upon the code received.

Graphical user interface

The visually pleasing, rational and intuitive GUI of the system is developed in Microsoft .NET Visual C++. The design is based on the traditional style of ECG paper plots with additional overlay displays and other features such as zoom, filter, database support etc. based upon proposals of cardiologists. The software is connected with database via ODBC driver. The following rules (Sumathi et al., 2007) are respected in design phase of GUI:

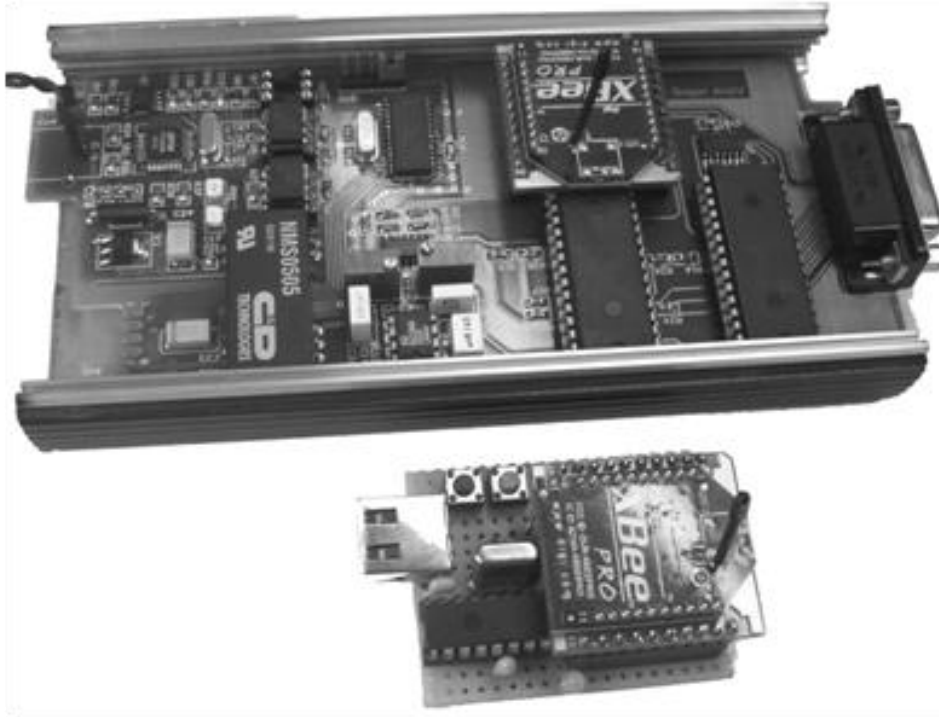1. To be intuitive and simple to use.
2. To be visually pleasing.

Figure 4. Appearance of prototype of the wireless ECG device.

3. To be aesthetically satisfying.
4. To be compatible with other Windows applications.

In this way a simple and intuitive manipulation is achieved and user training is faster. A sample of GUI is shown in Figure 5, with a description of the icons and dialogs. Monitoring of ECG waveform starts by clicking on the "start" ► icon. Depending on the lead selected, the PC sends an appropriate byte to the microcontroller which through hardware multiplexing selects the appropriate lead. If a user chooses to record a waveform, the dialog for adding a new patient appears. Then a user can either select a patient from the existing patients' database or add a new one. The dialogs described earlier are presented in Figure 5. The database automatically creates a unique name and path of the file where recorded waveforms were going to be saved.

The main frame ECG graph covers a 6s time interval as per cardiologists' request. The grids on the screen are placed in accordance with conventional grids on ECG paper. The waveform of the selected lead is shown in green on the screen during the process of monitoring. Users can record samples of the waveform in two ways:

1. By clicking on the "record" ● icon, the color of the waveform is changed into red and, after time interval of 6 seconds, it returns to green, but the recorded waveform appears in the auxiliary frame in the top right corner of the screen.

2. By clicking on the "6-" icon; the waveform does not change color on the main frame, but the waveform of the previous 6 seconds before the icon is clicked appears in the auxiliary frame. It is a very useful way to record the waveform when the user has already noticed some irregularity or anomaly in it and needs to conserve the graph for analysis.

The process of recording ECG waveforms is repeated for each of twelve leads which the user can select by clicking on a channel icon as shown in Figure 5. The icons of the leads whose waveforms are recorded in the system are outlined. The waveform of a recorded lead can be overwritten as many times as required. The monitoring process can be stopped by simply clicking on the "stop" ■ icon. This enables the "save" icon and the recorded waveforms can be written to file.

The recorded waveforms can be recalled from the database by selecting the appropriate patient sequence record. By clicking on a lead icon, the waveform of the selected lead appears in the auxiliary frame. The waveform can be copied to the main frame by clicking on any point inside the auxiliary frame.

There is a variety of icons in the toolbar such as: "zoom", "print" and the 50 Hz band stop filter icon which is described below. The patient is not isolated from the electro-magnetic interference of the public power network frequency which can impact on the ECG signals of the patient. A digital band stop filter is included in the
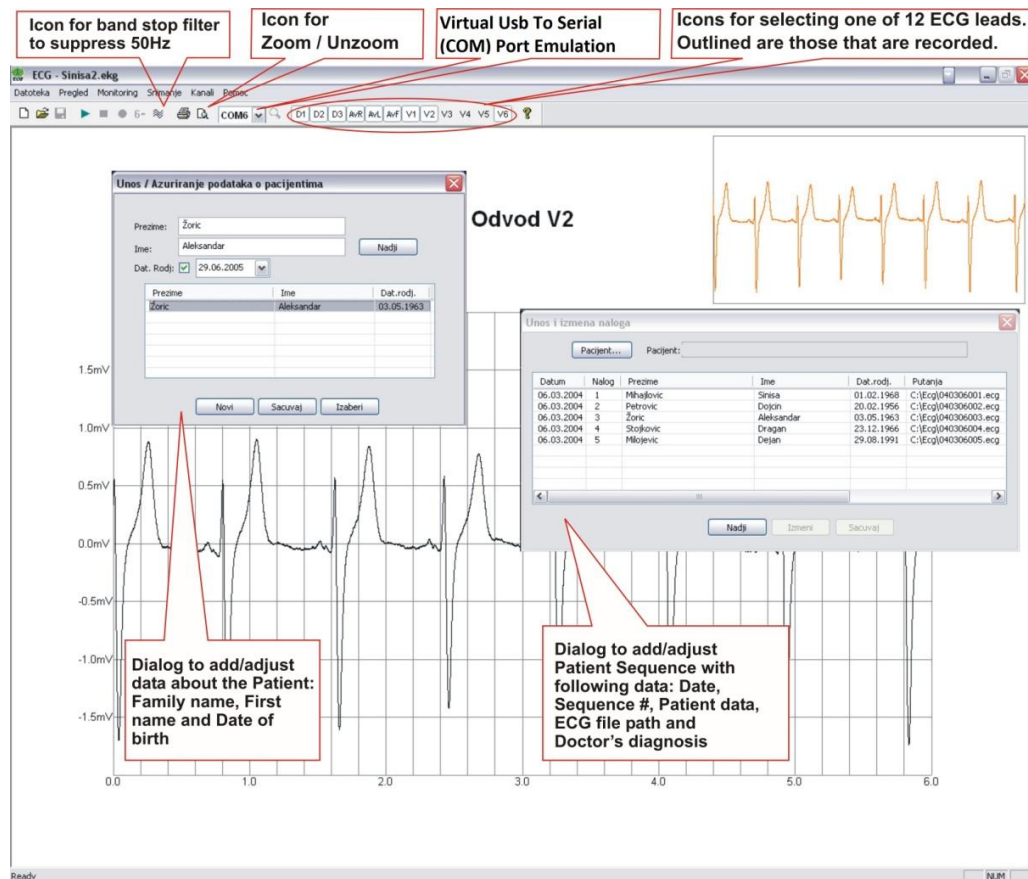
Figure 5. Screen shot of the ECG screen with descriptions.

software to suppress this noise. The requirements for band stop filter were:

1. Attenuation to be at least 50 dB at 50 Hz
2. Band stop bandwidth to be from 47 to 53 Hz
3. Order of filter to be as low as possible

This last requirement is very important because the hardware ECG device could be connected to any PC computer, not necessarily the latest generation. The band stop digital IIR filter using second order Butterworth transfer function is selected, which is given by the formula:

$$H(z^{-1}) = \frac{0.9807 - 1.8577 z^{-1} + 0.9807 z^{-2}}{1 - 1.8577 z^{-1} + 0.9615 z^{-2}} \qquad (1)$$

As can be seen from this equation, the number of mathematical operations for calculation of one output sample is small, which enables real time functioning of the filter.

The magnitude response of the digital band stop filter, which is used in the software, is shown in Figure 6. The sample rate of the ECG signal is determined by hardware constraints, and it is set at 960 samples per second. During a time interval of 1/25 of a second (refresh rate of the screen) about 40 samples are copied from the serial input buffer to a temporary storage buffer for samples to be drawn on the screen. The coordinates of the latest 40 sample points are then calculated and drawn on the main screen. Refreshing the waveform on the screen is executed only for the part of the main screen (1/150th of the screen's width) where the latest group of samples is to be drawn. The average time needed to plot one single sample on the main screen is of the order of one millisecond, which is more than enough even for the additional 5 multiplications and 4 additions required to execute the band stop filter if selected. Personal Computers of Pentium class one (100 MHz and above) or higher can handle real time rendering of the ECG signal described earlier.

Experimental results and exploitation

As stated in the previous chapters, a prototype of the described device that implements all of the
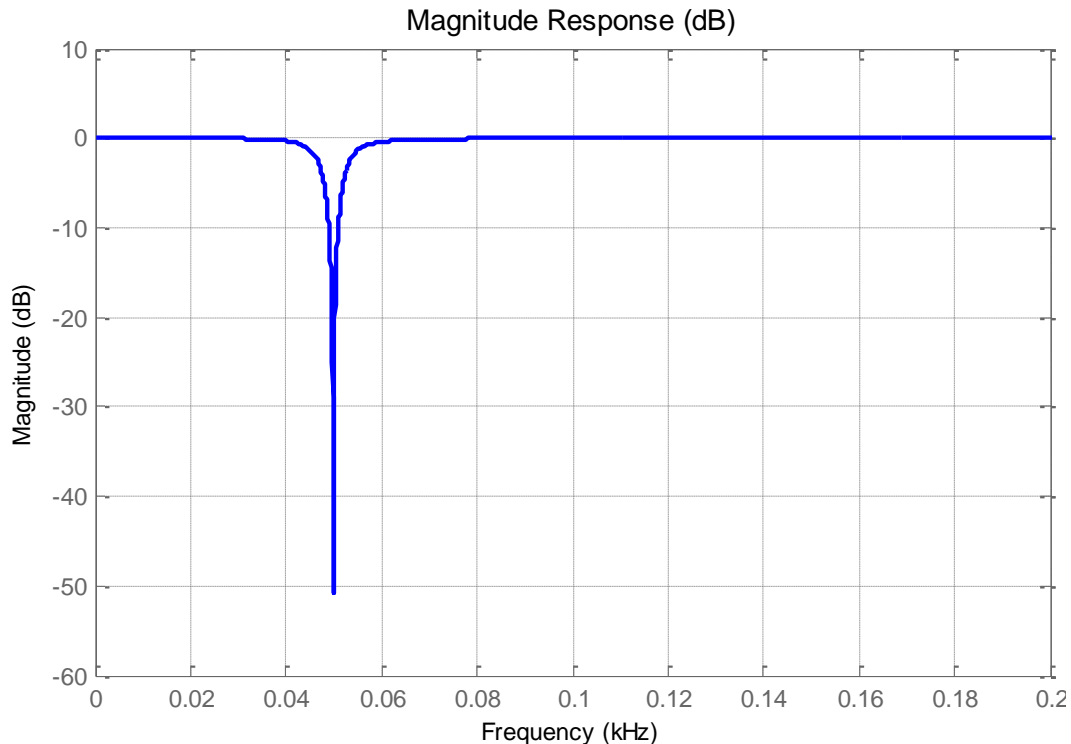
Magnitude Response (dB)

Figure 6. Magnitude response of the IIR band stop filter using 2nd order Butterworth transfer function (Equation 1).

aforementioned capabilities has been developed. Using the PS420 multi-parameter patient simulator (Fluke), the gain and offset (base-line) of the device are calibrated and then tested at various simulated ECG signals. Simulation of different intensity of ECG signal, heart rates and different heart diseases is very helpful for checking the accuracy of the device. For example, replication of normal sinus rhythms from simulator with a QRS width of 40 and 80 ms enables measurement QRS width in the zoomed ECG screen shot. It was found that the relative measurement error do not exceed ± 5%. The real low and high cut-off frequencies of the ECG amplifier were determined by a function generator. Both cut-off frequencies were approximately measured by changing the frequency of the sine signal, whose amplitude was 2 mV, ranging from 0.1 to 70Hz. In comparison to the amplitude of the signal at central frequency of 28 Hz, attenuations of -3dB were measured at frequencies of 0.3 and 62 Hz. The measured cut-off frequencies are approximate to calculated ones.

We also measured the attenuation of the Butterworth band stop IIR filter. The 50 Hz noise induced from AC public network is measured with and without filter in the absence of ECG signals. It was found that the band stop filter suppresses the frequency component of 50 Hz more than 45 dB. This ECG device has been used in City Medical Institute of Emergency in Belgrade. Owing to support of the database, a lot of reports with numerous

real ECG records were made and used for analysis. Obtained records are compared with calibrated records obtained by the ECG equipment of the Institute. Extremely high degree of agreement of both results is confirmed by cardiologists due to clarity and legibility of the ECG records. The presentation of a printed report of our ECG system is shown in Figure 7.

During the exploitation of our wireless ECG system, the transmission reliability is tested at different distances in the presence of standard consumer electronics, for example, cordless phones and Wi-Fi devices in operating mode in the same frequency band that may have negative affects on data transmission of ECG. The user did not note any error in either data transmission or data loss during one year. Unlike the conventional devices, the new device with database support enables evidence and searching through different measurements of ECG segments. A cardiologist may enter into database the description and measurements of ECG segments for the patient's signal (for example, ST depression 3 mm in V1, QRS segment in D3 20 ms, etc). Thanks to the measurements and obtained diagnoses, the broader analysis can be performed like correlation of some diagnoses to the width of some segments etc. As the signal are digitalized and stored into computer memory, the digital signal processing methods can be applied in order to perform automatic segmentation of the signals or to extract specific properties of waveforms.
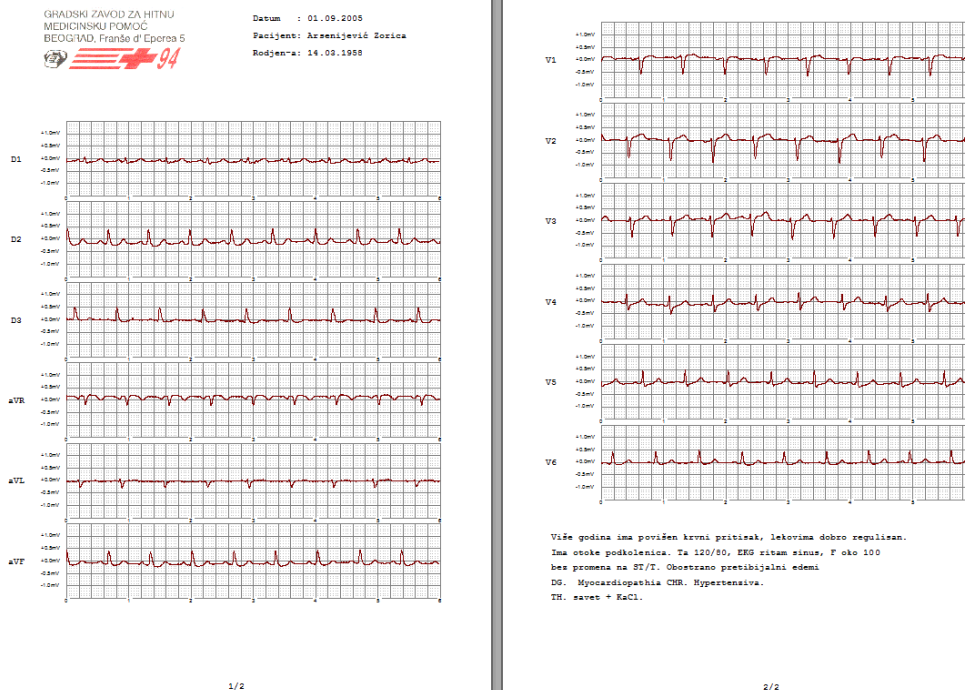
Figure 7. The print-preview screen of an ECG report.

DISCUSSION

The main advantages of ECG described in this article are powerful user friendly GUI with database support, the possibility of recording and printing up to 12 ECG lead with diagnose comments of cardiologist, portability and excellent readability of ECG waveforms. This ECG device is superior to many others described in literature. For instance in comparison to for example, (Singh et al., 2008) Microchip, microcontroller is used for realization of ECG device in the same way like in our solution. However, the functional performance of this solution is enormously reduced because it uses only one ECG lead for monitoring and recording. This is why this solution may serve only as a useful instructive and educational device. The solution in the study of Ekström (2006) has a serious limitation of maximum sample frequency which is about 400 Hz defined by bluetooth maximum data rate. Because of that this system is more suitable for patient monitoring but it is not applicable for diagnostic purposes. Limited range of about 10 m for bluetooth device is also a serious disadvantage of this solution, especially for long distance applications.

Similar ECG to the previously mentioned solutions is published in the article (Ming et al., 2002). The price of realization of this ECG is low and that is advantage in comparison to the other ECG solutions. However, it also provides the monitoring for only one ECG channel. A good solution of a portable wireless ECG device which has holter capabilities is presented in Lucani et al. (2006).

Since it uses Bluetooth capabilities this ECG device is not suitable for long distance applications. On the other hand the authors only partly considered the ECG because they did not describe the GUI interface, which is one of the most important parts of device.

The wireless ECG solutions described in Park et al. (2006) and Torfs et al. (2010) represent ultra low power ECG systems which operate with only 30mW and 170µW, respectively. Our wireless system consumes a much higher energy, mainly due to XBee RF module. However, it can be used in applications for much long distance. The wireless ECG system described in this article has been developing for long time. This developing has been made in accordance with new technological achievements as well as with user (cardiologist) requirements. Owing to the contemporary approach to device design, this ECG can be easily modified by adding new advanced functions in the GUI such as FFT or STFT analysis of the ECG waveforms with window displays. Future development of described ECG will be devoted to implementation of remote diagnostic via global network in telemedicine applications.

CONCLUSION

It is well known that electronics and PC based system with the corresponding software represent today the base for development of new medical devices. The modern portable system for wireless electrocardiography,

proposed in this paper, is developed using virtual instrumentation concept, meeting medicine standards and reaching the practical everyday needs.

In comparison to the conventional ECG, there are several advantages of the presented approach in this work. These advantages represent the new trace of medicine diagnostic developments and they will widely take place in everyday usage. The first one is wireless oriented medical system, which will enormously facilitate and make faster medical examinations in distance circumstances, as well as in home ones. Closely related to the first advantage is the portability. The portability without cabling enables usage of device almost under all conditions. This is one very important advantage, not only for contemporary medical needs, but for future medical equipment as well. It is expected that portability concept leads to development of personal medical equipments, which will enable people to connect themselves to large remote medical center and to use powerful diagnostic abilities, according to their personal needs. The main advantage of the system presented, compared to a conventional ECG device, is its software orientation. The software of device can be changed, extended or improved according to the user needs. New functions or any change can be added to the existing software quickly and cheaply. At last, in comparison to the conventional ECG, the proposed device may be connected to any modern information system, either to memorize the measured data or to process them for better diagnosis.

Although, the software plays a central role in the virtual instrumentation concept, the hardware module, described in this article, serves for processing of the heart bio-potentials. It may be the base for development of some other kinds of ECG devices. Special consideration in this work is devoted to the analysis of the software requirements in accordance to the virtual instrumentation concept, as well as, to the matching of the virtual instrumentation requirements to the user needs.

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REFERENCES

Chiulan T, Pantelimon B (2008). Power transformer units condition assessment using virtual instrumentation. Electronics and El. Eng. J. Kaunas Technol., 6(86): 97-100.

Dunbar M (2001). Plug-and-play sensors in wireless networks. IEEE Instrum. and Meas. Magaz, 4(1): 19-23.

Ekström M (2006). Small wireless ECG with bluetooth communication to a PDA. A MSC thesis in electron. sci. performed at the Dep. of Comp. Sci. and Electron. - Mälardalen University, Sweeden, pp. 1-32.

Garrett PH (2002). Multisensor Instrumentation 6 [sigma] design - defined accuracy-computer integrated-measurement systems. John Wiley and Sons. Inc. pp. 1-209.

Ko CC, Chen BM, Ramakrishnan SYV, Cheng CD, Zhuang Y, Chen J (2001). A web-based virtual laboratory on a frequency modulation experiment. IEEE Trans. Sys. Man Cyber, 31(3): 295-303.

Lucani D, Cataldo G, Cruz J, Villegas G, Wong S (2006). A portable ECG monitoring device with bluetooth and holter capabilities for telemedicine applications: Proc. of the 28th IEEE EMBS Ann. Int. Conf. USA, pp. 5244-5247.

Ming LY, Yiu HY, Hang LW (2002). Bluetooth-enabled electrocardiogram monitoring GBA system. Final year Project (2002-2003), The Hong Kong University of sci. and tech., Project I.D. No.: MWH3-02.

Park C, Chou PH, Bai Y, Matthews R, Hibbs A (2006). An ultra-wearable, wireless, low power ECG monitoring system. Proc. IEEE BioCAS, Nov 29 - Dec 1, The British Library.

Singh G, Chandra H, Satsangee SP (2008). Fabrication of USB based electrocardiogram machine. XXXII Nat. Sys. Conf.-NSC, pp. 48-51.

Sumathi S, Surekha P (2007). LabVIEW based advanced instrumentation systems. Springer - Verlag Berlin Heidelberg, pp 1-728.

Torfs T, Yazicioglu RF, Sunyoung K, Hyejung K, Van HC, Buxi D, Romero I, Wijsman J, Masse F, Penders J (2010). Ultra low power wireless ECG system with beat detection and real time impedance measurement. Biomed. Circ. and Sys. Conf. (BioCAS), IEEE, pp. 33-36.

Yao KC (2008). Single input virtual digital multi-meter design and implementation, Int. J. Innov. Comput. Inf. Control, 4(12): 3101-3110.

Žorić AČ, Ilić SS (2005). PC-based electrocardiography & data acquisition, Proc. Int. Sci. Conf. TELSIKS, IEEE, pp. 619-622.

Žorić A, Đorđević B, Martinović D, Obradović S (2004). Dual channels virtual thermograph for qualitative differential thermal analysis of materials. Proc. Int. Sci. Conf. UNITECH-04 – Bulgaria, I, pp. 130-137.