A WEARABLE SYSTEM FOR REAL-TIME OUTPATIENT ECG MONITORING

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НОСИМА СИСТЕМА ДЛЯ АМБУЛАТОРНОГО МОНІТОРИНГУ ЕКГ В РЕАЛЬНОМУ ЧАСІ

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Functional state of the cardiovascular system is an important factor for human physical well-being. To perform analysis of the cardiovascular state, the wearable continuous ECG monitoring system is essential. In this paper, a wearable ECG monitoring system based on IoT is proposed. The systems architecture is presented. Wearable devices design employs few optimal components for the acquisition of acceptable ECG signal. The R peaks corresponding to each heartbeat, and T waves, a morphological feature of the ECG are detected. It enables to perform heart rate and heart rate variability analyses, as well as extract, store and analyze the long term ECG measurements.

Keywords*: health monitoring system, wearable device, ECG signal acquisition, QRS-complex detection*

1. Introduction

Cardiovascular diseases (CVD) are the leading cause of fatalities representing 30% of all global deaths. Due to inadequate preventive measures, CVD related fatalities continue to rise. Electrocardiogram (ECG) is widely used to monitor heart function. At present, an expert cardiologist analyzes short-duration ECG plots to detect abnormalities. Since certain kinds of heartbeat arrhythmias occur sporadically over an extended period, patients require long term monitoring. Monitoring of person ECG changes is important as far as preventive events of pathology cardiovascular diseases.

The recent technologies as a Big Data, Internet of Things (IoT), mobile technologies, and wearable devices step-by-step take up the art of cardiovascular diseases diagnostic to a new level. In this context, the goal is development of wearable ECG monitoring systems.

The human computer interface systems [1] are widely used to extract the context from the implicit information received, collected, processed by wearable devices, which characterizes the situation of a person or place related to a conversation, helps us transfer ideas to each other and respond accordingly [2, 3]. X. Li et al. [4] presented a wearable heart rate monitoring system. They have developed the wearable device for real-time acquisition and analysis of heart rate signal. Data is stored on the server and it's available for viewing status. Data transmission is carried out using a smartphone. T.O. Meservy et al. [5] developed the mobile health monitoring application. It includes a real-time signal obtaining, ECG signal processing, visualization, and data management. M. M. Baig et al. [6] presented a comprehensive survey of more than 120 wireless and wearable ECG monitoring systems for adults. The results of the review show the main advantages and drawbacks of deployed ECG monitoring systems including short battery life, lack of user acceptability and medical professional's feedback, and lack of security and privacy of essential data. Moreover, in spite of the wide variety of academic works, the ECG monitoring systems still require improvements to deliver the best quality of monitoring and data processing.

In this paper, the IoT wearable system for ECG monitoring with signal acquisition, processing for QRS-complex detection are proposed. Section 2 describes the health monitoring system architecture and ECG wearable device configuration. In Section 3 the system development process and techniques of ECG signal acquisition and processing for QRS-complex detection are discussed. The result of ECG monitoring system implementation and QRS-complex elements detection is present in Section 4. Section 5 contains the paper conclusions and future work.

2. Health Monitoring System Design
2.1. Health Monitoring System Architecture

The architecture of a wearable biomedical information monitoring system is represented by three main components, presented in Fig.1.

The first necessary component is various types of wearable devices and sensors that perceive the physical signals of the human body, which are directly wearable devices.

Biomedical sensors can also be directly integrated into garments and accessories, thus forming a wearable body area network (WBAN) [9].
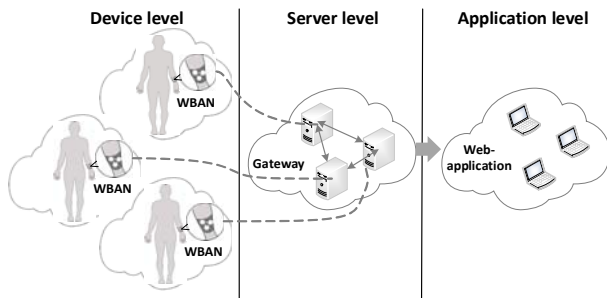
Fig. 1. Health monitoring system architecture
(Adapted from [7,8])

Fig. 2. Devices configuration

WBAN is a subset of wearable biomedical sensors and systems that can be used to control, stimulate, treat, and replace the biological and physical functions of the human body [10].

Such integration requires consideration of two general limitations when developing a biomedical information monitoring system: limited memory capacity of the device and limited power capacity. These restrictions affect the storage, processing and transmission of data:

1. Data received by the device cannot be stored on it for a long period of time and must be transferred to another device / server.

2. When developing a wearable system for monitoring biomedical information, energy-saving data processing algorithms have an advantage.

These factors determine the need for a second component of the system — external storage, processing, and data transfer devices. Data can be transmitted directly from sensors or using external devices with more computational power (e.g. a smartphone). Continuous processing of data in conjunction with the operation of the wireless network adapter consumes a lot of energy resources, which can quickly be exhausted and as a result, disrupt the execution of its direct purpose. External devices usually perform primary signal processing and transfer data to the next level (cloud storage, servers) for further analysis and long-term storage.

As an external device, WBAN can control the physiological parameters of the human body and be used for their collection and transmission.

The third component is represented by cloud storages, servers. Since wearable biomedical information monitoring devices and base stations have limited resources, the resulting data is usually sent to servers, cloud storage for processing and long-term storage.

2.2. Wearable Device Configuration

A wearable ECG device is responsible for collecting ECG data from human skin, and then transmitting this data to an access point through a wireless channel. As shown in Fig. 2, the ECG monitoring node in our system mainly includes: (1) a sensor module; (2) controller module with wireless adapter; and (3) power module.

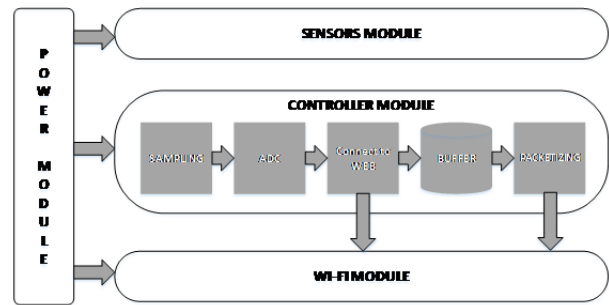(1) Sensor module is the core component of the monitoring device, which is responsible for obtaining human ECG data.

Recorded physiological signals usually consist of a source signal and noise. Noise occurs at each stage of data collection, before they are digitized. Noise of the power supply module, muscular noise, noise of the analog-digital converter suppresses ECG signals.

Power line interference is an electromagnetic field from a power line, causing sinusoidal interference at 50 or 60 Hz.

The noise causes problems when interpreting low frequency signals such as an ECG. Consequently, there are many methods have been used to denoising of power line noise in ECG signals [11]. Thus, S. Pooranchandra and N. Kumaravel [12] proposed a nonlinear function of wavelet coefficient shrinking to remove the power line frequency, in [13] they developed an approach based on adaptive noise removing; K. Ziarani and A. Konard [14] proposed the technique to subtract the power line interference from the ECG, which employs to almost all possible causes sampling frequency and interference frequency.

This module filters and amplifies the received ECG signal. The frequency of the ECG signal lies between 0.5 Hz and 100 Hz [15] and this must be taken into account when choosing the method of filtering the ECG signal. To eliminate this kind of noise, an Infinite impulse response (IIR) filter can be used. The equation for this filter can be represented as follows (Eq. 1).

$$y[n] = \sum_{k=0}^{M} b_k x[n-k] + \sum_{k=1}^{N} a_k y[n-k], \qquad (1)$$

where M is the feedforward filter order; N is the feedback filter order; b_k are the feedforward filter coefficients; a_k are the feedback filter coefficients; $x[n]$ is the input signal; $y[n]$ is the output signal.

To eliminate the baseline wander in the ECG, which can be caused by breathing, electrode impedance, body movement, various methods are used. Often used is a base level interference suppression method based on a Butterworth bandpass filter. After filtering, the signal is amplified using an operational amplifier.

(2) A controller module with a wireless adapter is used to process and transmit the received ECG signal. In the controller module, it is possible to set the necessary parameters for additional signal processing, its buffering, packaging for further transmission via a wireless channel. This provides fast and convenient access to the

Internet for transmitting ECG data in real time to a server or IoT cloud storage.

(3) Power module provides reliable power supply of each module in the ECG monitoring device.

2.3. Detection of a QRS complex and measurement of heart rate

Detail waves of ECG signals are important information for health/medical application. Usually, the following elements can be distinguished on an ECG, as shown in Fig. 3, among them are the P, Q, R, S, T wave. Sometimes we can see the inconspicuous U wave. The P wave reflects the process of depolarization of the atrial myocardium, the QRS complex - depolarization of the ventricles, the ST segment and the T wave reflect the processes of repolarization of the ventricular myocardium.
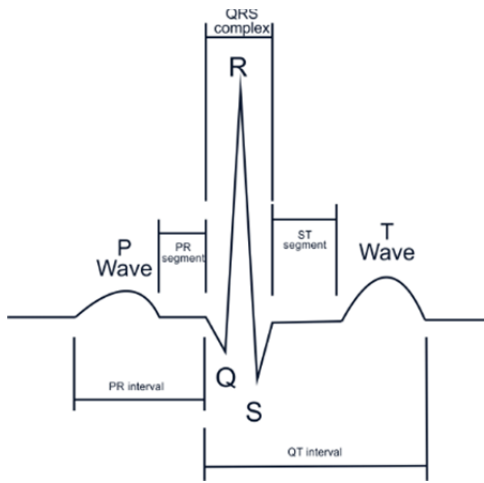

Fig. 3. Elements of ECG complex

The QRS complex can be identified using a common method for determining ECG parameters. R-peak is easier to distinguish from noisy components, as it has large amplitude (Fig. 4).
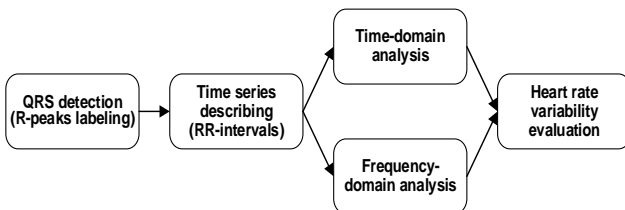

Fig. 4. The general stages of heart rate variability evaluation process

After the pre-processing, variable threshold method can be used to further detect the R-peak. The R-peaks allow heart rate and heart rate variability analyses to be performed, extracting the wanted long term physiological measurements. The formula for variable threshold value is defined as follows.

$$V_{TN} = [x(n) - x(n-1)] \cdot 70\%$$

The threshold makes it possible to differentiate R peak from the baseline, which is corresponding to 70% of ECG peak data detection. We were able to find QRS complex based on the detected R-peak. Detection of QRS complex is particularly important in ECG signal processing. In our system, we used a robust real-time QRS detection algorithm [16]. This algorithm reliably detects QRS complexes using slope, amplitude, and other information. The information obtained from QRS detection, temporal information of each beat and QRS morphology information can be further used for the other ECG parameter detection. In order to detect QRS complex, the signal is initially passed through a band-pass filter. It is composed of cascaded high-pass and low-pass filters. Subsequent processes are five-point derivative (Eq. 2), square (Eq. 3), moving window integrator (Eq. 4), and detection.

$$y(nT) = \frac{2x(nT) + x(nT - T) - x(nT - 3T) - 2x(nT - 4T)}{8} \quad (2)$$

$$y(nT) = [x(nT)]^2 \quad (3)$$

$$y(nT) = \frac{1}{N}[x(nT - (N-1)T) + x(nT - (N-2)T) + ... + x(nT)] \quad (4)$$

The instantaneous heart rate computed directly from R-R interval. In clinical settings, heart rate is measured in beats per minute (bpm). So, the formula for determining heart rate from RR interval is given below (Eq. 5).

$$Heart\_rate = \frac{60,000}{RRInterval(ms)} \quad (5)$$

3. Implementation Result
3.1. EEG wearable Device Specification

EEG wearable device hardware includes follow components: ESP-WROOM-32 DEV KIT, OLIMEX SHIELD-EKG-EMG, Breadboard MB-102 830 holes, SHIELD-EKG-EMG-PRO, ECG-GEL-ELECTRODE, USB 2.0 Micro B Cable, Male/Male Jumper Wires 150mm, Poweradd Slim2 5000mAh Portable Charger Power Bank.

3.2. ECG signal acquisition technique

Place the electrodes on the body as follows Fig. 5: white electrode on the left arm, red electrode on the right arm, black electrode on the left leg.

The network of short-range and long-range communications for ECG monitoring is used. The stages of network hardware configuration using Wi-Fi router are defined as follows: Wi-Fi setup, turn on DHCP, connect a router to computer, edit an ESP32 firmware (change IP address, SSID, password), connect ECG electrode to your body, run special Python script and get the ECG signal.
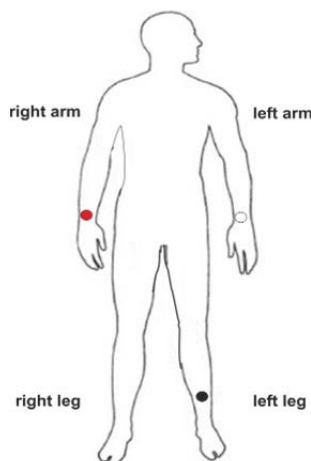
Fig. 5. The electrodes location
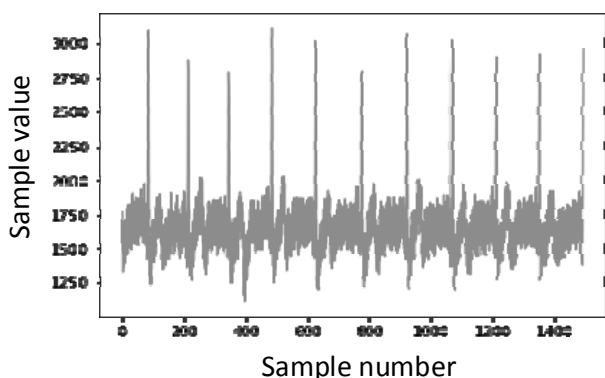
Achieved ECG signal is present in Fig. 6.

Fig. 6. Fragment of ECG signal

The frequency of a signal measures the cyclic rate and is measured in Hertz (Hz). A frequency of 1 Hz means a signal repeat itself every one second. The heart produces electrical activity, which records by electrodes as a signal. The sinoatrial node beat about 50 to 90 beats per minute. That means the heart has a frequency of 1 Hz at this heart rate. According to this, the ECG elements (P, QRS, and T) will occur at or above this frequency.

The ECG signal obtained from multiple sources. The recording includes signals from several electrodes on the skin, which capture more than just the electrical activity of the heart. The primary electrical elements captured are the myocardium, muscle, skin-electrode interface, and external interference.

3.3. ECG Component Frequencies

The basic frequencies of the important components on the ECG can be presented as follow: heart rate $0.67 - 5$ Hz, P-wave $0.67 - 5$ Hz, QRS $10 - 50$ Hz, T-wave $1 - 7$ Hz, high-frequency potentials $100 - 500$ Hz. The basic frequencies of the artifacts and noises on the ECG can be presented as follow: muscle noise $5 - 50$ Hz, respiratory noise $0.12 - 0.5$ Hz, external electrical activity 50 or 60 Hz (A/C mains or line frequency), and other

electrical activity, typically, >10 Hz.

The skin-electrode interface needs special attention, as it is the largest source of interference, producing a DC component about 200-300 mV. Comparing this to the electrical heart activity, which is in the range of 0.1 to 2 mV. The interference seen from this component is increased by motion, either person movement, or respiratory variation.

For the time-series analysis of the heart rate signal, are using intervals between the heartbeats and its variation over time. The most important of ECG signals analysis is to determine the position of the R-peaks since they correspond to the heartbeat and the position of other peaks and waves can be found relative to the defined R-peak. The R-peaks are detected using moving window integrator (Fig. 7).
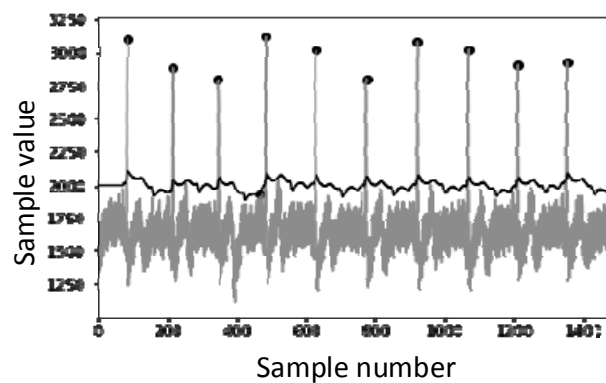

Fig. 7. Fragment of ECG signal with detecting R-peaks

From a signal processing the position of all R-peaks, RR-intervals between R-peaks and differences between adjacent RR-intervals are found. From these parameters, the analysis of the heart health state can be implemented and the potential heart state disorders will be predicted.

Thus, relatively stable real-time ECG signal is successfully monitored and diagnostic ECG elements, such as R-peaks, are detected.

Conclusion

In summary, we developed the wearable system for outpatient ECG monitoring. The architecture of ECG monitoring system is based on the three-level scheme. The configuration of ECG wearable device to provide healthcare service was designed. The acquisition and processing of ECG signal are presented. The diagnostic ECG elements, such as R-peaks, are detected. Analysis of continuous heart rate signal and procedures for extracting of heart rate parameters are described.

Future work will focus on monitoring additional health related parameters and implementing the anomaly detection techniques, and on improving system reliability and robustness for patient movement and connectivity losses.

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Білобородова Т.О., Скарга-Бандурова І.С., Дерев'янченко В.С. Носима система для амбулаторного моніторингу ЕКГ в реальному часі

Стан серцево-судинної системи є важливим фактором фізичного здоров'я людини. В багатьох випадках, для аналізу стану серцево-судинної системи потрібна носима система безперервного моніторингу ЕКГ. У цій статті ми запропонували варіант системи для амбулаторного моніторингу ЕКГ. Представлена архітектура системи. При проектуванні носяться пристроїв використовується кілька компонентів для отримання прийнятного сигналу ЕКГ. Піки R, відповідні кожному серцебиття, і Т-хвилі - морфологічна особливість ЕКГ. Це дозволяє проводити аналіз серцевого ритму і варіабельності серцевого ритму, витягуючи необхідні довгострокові вимірювання ЕКГ.

Ключові слова: система моніторингу здоров'я, носимий пристрій, сигнал ЕКГ, виявлення QRS-комплексу.

Белобородова Т.А., Скарга-Бандурова И.С., Деревянченко В.С. Носимая система для амбулаторного мониторинга ЭКГ в реальном времени

Состояние сердечно-сосудистой системы является важным фактором физического здоровья человека. Во многих случаях, для анализа состояния сердечно-сосудистой системы требуется носимая система непрерывного мониторинга ЭКГ. В этой статье мы предложили носимую систему для постоянного амбулаторного мониторинга ЭКГ. Представлена архитектура системы. При проектировании носимых устройств используется несколько компонентов для получения приемлемого сигнала ЭКГ. Пики R, соответствующие каждому сердцебиению, и Т-волны - морфологическая особенность ЭКГ. Это позволяет проводить анализ сердечного ритма и вариабельности сердечного ритма, извлекая требуемые долгосрочные измерения ЭКГ.

Ключевые слова: система мониторинга здоровья, носимое устройство, сигнал ЭКГ, обнаружение QRS-комплекса.

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