A Multi-channel ECG Acquisition System Based on FPGA

Yubo Zhu*, Xin'an Wangb, Changpei Qiu, Qiuping Li, Xuan Cao, Bing Zhou and Hu Wang
The Key Laboratory of Integrated Microsystems, Peking University Shenzhen Graduate School, Shenzhen, China
*a1901213030@pku.edu.cn; b, *anxinwang@pku.edu.cn

Abstract. To collect accurate human Electrocardiogram (ECG) signal in complex scenarios and use them for subsequent disease pathology analysis by our laboratory team, we have designed a multi-channel acquisition system with adjustable gain, easy portability, and adaptability to most applications. The whole acquisition system is divided into the Electrode Group, Analog Front End (AFE), and the Data Storage System (DSS). The AFE uses a secondary amplification circuit as well as band-pass filtering and notch filtering circuits. The data storage side is an FPGA-based system design that realizes the functions including AD conversion, real-time display, and storage of data. Experiments show that this system can realize multi-channel and portable acquisition and storage of ECG signal under complex scenarios.

1. Introduction
The human body is one of the most complex systems, and the ECG signal is quite complicated and contains a lot of health information about the human body, from which various physiological diseases can be analyzed, such as Diabetes, Atrial Fibrillation, Heart Attack, etc. It is another measurable physical signal of the human body in addition to sound, temperature and color [1]. Recently, with the popularization of embedded and in-depth research, as well as the enhancing of people's health awareness, portable ECG devices have received more and more attention and are widely used in home medical diagnosis and risk warning [2]. On the other hand, cardiovascular diseases are difficult to detect through the patient's external manifestations during the latent period. Their sudden onset makes it difficult for patients to receive timely treatment, leading to a higher mortality rate, so the ECG signal in the pathology of Cardiovascular disease research has greater medical significance, and all of this is based on the obtaining of the complete, standardized ECG signal [3][4].

Our team designed a Gain-adjustable, Eight-channel, and Easy-to-test ECG signal acquisition system. The second section is the analysis of human ECG signal. The third section introduces the system's overall framework, including the selection of Electrode Groups, AFE circuit design, and FPGA-based DSS design. The fourth section is experiments and results of the system. Experiments have shown that The system can realize the Multi-channel acquisition, real-time display and storage of human ECG signals in complex scenarios. At the same time, the acquisition's gain can be adjusted.

2. ECG signals analysis
ECG signal is a comprehensive reflection of the electrical activity of cardiomyocytes in the heart. Its production is closely related to the process of De-polarization and Re-polarization of cardiomyocytes. Data show that the heart is continually contracting and stretching rhythmically. Bioelectric changes
produced by myocardial agitation are reflected on the body surface through conductive tissue and body fluids around the heart. Regular electrical change activity also occurs in each heart cycle[5].

According to the standards established by the American College of Cardiology, the amplitude range of standard ECG signal is between 10μV-4mV, the frequency range is within 0.05-100Hz, and 90% of the ECG spectrum energy is concentrated between 0.25-35Hz. Therefore, our team designed the band-pass filter with cut-off frequency of 1-450Hz. There are two reasons for setting the lower limit of the cut-off frequency of the band-pass filter slightly higher than the standard: one is to consider the actual AFE filter performance is not ideal, and second is to consider the impact of baseline drift on the system, in order to suppress baseline drift, the cut-off frequency must be set within a reasonable value. Otherwise, it will not have the effect of suppressing baseline drift. The upper limit of band-pass frequency is set beyond the standard is to make it compatible with the collection of human electromyogram (EMG) and facilitate other projects in the laboratory. The ECG signal is weak, unstable, low frequency, and random. Due to the inhomogeneity of the human body and external signals' influence, the ECG signal easily changes with the change of external interference[5]. All of this presents many challenges for the design of the AFE. After many debugging and revisions, our team finally realized a Multi-channel, Gain-adjustable and real-time displayable acquisition and storage system for ECG signal in complex scenarios.

3. System structure
As shown in figure 1, the whole system consists of the Electrode Group, Analog Front End (AFE), the Data Storage System (DSS). The first part is the Electrode Group, which is divided into the Detection Electrode, Reference Electrode, and DRL Electrode. The ECG signal is input to the AFE through the multi-probe electrodes[1], and the AFE filters and amplifies the signal and outputs it to the ADC module, which is input to the FPGA development board after analog-to-digital conversion to realize real-time display and storage of data. Because the AFE is a multiplex output, a Control Module is required to control the ADC sampling[2].

![Figure 1. The structure of the ECG acquisition system](image)

Figure 2 shows the physical map of the system. The signal acquisition circuit enters the digital signal into the FPGA development board through the ADC module, thus realizing the data's real-time display and storage.

3.1. Electrode group
The Electrode Group consists of the Detection Electrode, Reference Electrode, and the DRL Electrode. All the electrodes are disposable ECG electrodes, Considering the safety, accuracy and cost of the experiment, we chose AgCl disposable electrodes, consisting of electrode buckles, conductive voltage-sensitive glue, silver chloride buckles and anti-mucous membranes. The shape is round and the diameter is 50mm, using AgCl as the sensing element, hydrogel as the viscous element to enhance the adhesion.
effect of the product and skin, thereby significantly reducing the problem of poor contact caused by patient’s activity. The material has good skin adaptability and connected to the ECG wire through an electrode buckle. For the experiment’s accuracy, the skin under the test was also cleaned and disinfected with alcohol before each experiment.

![Figure 2. Physical map of the system](image)

Figure 2. Physical map of the system

Figure 3 shows nine Detection Electrodes and a Reference Electrode, nine Detection Electrodes as differential input signals for the eight-channel AFE. PDE1-PDE8, respectively, is the positive differential input of eight channels, connecting the negative inputs of eight channels to induce an NDE Detection Electrode. The Reference Electrode is similar to the NDE in that the electrode connected by the eight-channel REF is the Reference Electrode RE. The Reference Electrode's purpose is to pull the human body and the system to a same reference voltage. The electrodes are connected to the AFE via a self-made VGA interface, reducing crosstalk between signals.

![Figure 3. Detection and Reference Electrodes](image)

Figure 3. Detection and Reference Electrodes

3.2. Analog Front End

The AFE contains a Detection Module, a Power Module, and a DRL Module. The Detection Module achieves amplification filtering of the ECG signal under the Power Module's power supply[6]. The DRL Module implements a feedback loop between the human body and the detection circuit, reducing interference from the common-mode signal.

3.2.1. Power module. The output voltage range of the op-amp is definitely smaller than the Voltage Range of its operating power supply. The waveform of the ECG signal must have a negative value relative to the common-ground-point, to ensure the collected ECG waveform's integrity and stability, dual power supply is selected. The adapter is directly connected to the household 220V AC voltage. It
produces a DC voltage of 5V connected by USB port-to-access Power Module to generates a DC voltage of +/-2.5V for the Detection Module and the DRL Module to work on.

3.2.2. DRL module. Since the human body is a good conductor, there will always be a common mode voltage generated by the 50Hz Alternating Current(AC) in the system working environment on the human body, this voltage value can reach dozens of millivolts, it has serious effects on ECG signal, which requires op-amps have a high common-mode suppression ratio[1]. The DRL Module is used to effective suppress common mode interference caused by the power frequency signal. The sampled human common-mode voltage is inverted and amplified through the DRL circuit and feed back to the right leg (RL), which reduces the human common-mode voltage, thus reducing the common-mode voltage caused by power frequency interference[7].

3.2.3. Detection module. The detection module consists of the Instrumentation Amplifier(IA) circuit, fourth-order Butter Worth filter circuit, Operational Amplifier(OA) circuit, and a Notch circuit.

Since the magnitude range of standard ECG signal is between 10μV-4mV, to make full use of the sampling accuracy of the subsequent ADC, the IA circuit and the standard OA circuit are selected to achieve adjustable amplification of the signal [1][3]. Figure 4 is the two-stage magnification circuit, 4.a is the IA circuit. On the one hand, due to the human body's inhomogeneity and the influence of human motion artifacts, the signal received has much clutter. On the other hand, by the influence of foreign electromagnetic signals, the ECG signal is easy to change with external interference. Therefore, Therefore, an IA circuit with high common-mode rejection ratio, low drift, and high input impedance is selected for the first stage of the detection circuit. 4.b is a standard OA circuit, Rc is an adjustable resistor, to achieve the function of amplification adjustable. IA circuits and OA circuit cascades can achieve 10-2600 times magnification.

Figure 4. Physical map of the system

Gain formula:

\[ G_{\text{total}} = G_{\text{IA}} \times G_{\text{OA}} = \frac{R_s}{R_i} \times (1 + 2 \times \frac{R_1}{R_G}) \times \frac{R_c}{R_G} \]  

\[ G_{\text{total}} - \text{ the total gain} \]
\[ G_{\text{IA}} - \text{ the gain of Instrumentation Amplifier} \]
\[ G_{\text{OA}} - \text{ the gain of Operational Amplifier} \]

The ECG is a very weak signal with a voltage in the mV range, and the main frequency range is between 0.05 and 100 Hz, so the ECG signal is extremely susceptible to external interference and noise during the detection process, For example, the slight movement of the human body causes a change in the impedance of the contact between the electrode and the human body, besides, the Indoor lighting and power equipment affect the distributed capacitance of the human body caused by the power
frequency interference and its harmonic interference. For the above two cases, the filter circuits shown in Figure 5 are designed[6][8].

![Filter Circuit Diagrams]

**Figure 5.** Filter circuit

Figure 5.a shows the second-order Butterworth filter for 1-450Hz filtering, the effect of connecting two second-order Butterworth filters in series in the AFE is equivalent to a fourth-order Butterworth filter.

Cut-off frequency formula of Second order band-pass filter:

\[
f_{hpf} = \frac{1}{2\pi \sqrt{R_1 C_1 R_2 C_2}}
\]

(2)

\[
f_{lpf} = \frac{1}{2\pi \sqrt{R_1 C_1 R_2 C_4}}
\]

(3)

Figure 5.b shows the 50Hz dual T-type notch filtering circuit, which is designed to limit the impact of power frequency interference and its various harmonics on the entire circuit.

Center frequency formula of 50Hz dual T-type notch filter:

\[
f_{notch} = \frac{1}{2\pi R_5 C_5}
\]

(4)

3.3. Data storage system

To meet the requirements of specific usage scenarios and make full use of the ADC sampling accuracy, our team selected the AN706 module and realized the functions of AD conversion, real-time display, and storage of eight-channel data under the control of the FPGA development board[9]. The ADC model of the AN706 is AD7606. The AD7606 is an integrated eight-channel synchronous sampling data acquisition system with an on-chip integrated output amplifier, overpressure protection circuit, second-order analog anti-aliasing filter, analog multiplexer. The sampling accuracy is 16bit, and all channels have been up to 200kSPS throughput sampling. Using a single power supply of 5v, it can handle the input signals of +/-10V and +/-5V, the simulated input impedance is 1M ohm at any sampling rate, it is connected to the FPGA development board via a 40-pin 2.54mm pitch header, and to the AFE via an 8-way SMA interface and a 2.54 pitch 16-pin header.
Figure 6. Data Storage System

Figure 6 shows the framework of the DSS. After the system is powered on, the AN706 module implements AD conversion and digital signal readout under the control of the Control Module, which is also responsible for output control signals to the OMUX module, thus converting the single-channel output signal of the AN706 to an eight-channels output signal to RAM Array Module[2]. The OMUX module also transmits the signals of eight-channels to HDMI at the same time, which will eventually display the signal on the screen in real time via TMDS transmission. The WR_EN Module is responsible for controlling whether digital signals are written to the SD card in SPI mode. Figure 7 shows the workflow diagram for the entire system.

Figure 7. Data Storage System

4. Experiments and results
In order to verify the feasibility of the equipment, the experimental device was tested on a number of volunteers. The test subjects were asked to sit still while being tested, attach the electrodes to the subject
in the same way as the twelve leads of the ECG test. Respectively, V1: chest bone right edge fourth rib, V2: chest bone left edge fourth rib, V3: V2 and V4 wire mid-point, V4: left collarbone midline and fifth rib intersection, V5: The front line of the left armpit is the same level as the V4, the central line of the left armpit is the same level as the V4, the rear line of the left armpit is the same level as the V4, and the V8: the spine is at the same level as the V4. The eight channels of ECG signals are observed from the screen, the acquisition button is pressed when the signal quality is high, the data is stored on the SD card, and the data saved from the FPGA development board is digitally filtered by PyCharm.

Before the measurement, cleaning the measured position with alcohol and trying to keep the subject stationary to avoid interference of the ECG signal by large movements.

Figure 8 shows the signal spectrum before and after PyCharm processing. it can be seen that the signal is more energetic in the 1-100Hz band, and is retained to the maximum extent to ensure the integrity of the signal.

![Figure 8. Signal Spectrum](image)

Figure 9 shows the signal waveform before and after PyCharm processing, from which can be seen that the signal interference is considerable and there is more clutter. Although the ECG signal characteristics are retained, the environment and power frequency current have a relatively large impact on the signal of the ECG signal.

![Figure 9. Signal Waveform](image)

Found through multiple tests:
- During the test, the experimental subject must be stationary. If the subject limbs or body is in a non-stationary state, the signal interference is considerable, and even the waveform has noticeable distortion.
- Many tests have found that although we have designed the circuit to suppress the power frequency alternating current influence on the system, including the DRL circuit, 50Hz notch
circuit, its impact on the entire system still exists, from figure 8 can be seen that the 50Hz band of energy still exists and is more concentrated. Although the basic characteristics of the ECG signal still exists, but still should try to avoid its impact on the measurement, lithium batteries can be used to power the system, which is convenient to move and can also reduce the power frequency interference.

5. Conclusion
This paper describes the design of a Gain-adjustable, Eight-channel ECG signal acquisition system, illustrating the selection of front-end Electrode Groups, AFE circuit design, and AD conversion module, waveform display, digital signal storage. The experimental results show that the system can realize the function of Multi-channel acquisition, Gain-adjustment, storage and real-time display of ECG signal, and the AFE has a certain suppression effect on the interference of the power frequency signal. Compared with other ECG acquisition systems, it is not easy to occur the phenomenon of baseline drift, the integrity of the signal can also be retained to the maximum, after simple software low-pass filtering can be obtained a higher degree of integrity of the ECG signal, laying the foundation for subsequent research on ECG signals.

Acknowledgements
This work was supported by the Special Fund for the Shenzhen (China) Science and Technology Research and Development Fund (JCYJ20200109120404043).

References
[1] Syahida E, Shafii M. ECG Acquisition With Labview Interface[J]. Desalination, 2006, 185(1):391-397.Cheung F 2011 TCM: made in China Nature 480(7378) pp 82-3
[2] Qin Zhenhua, Xia Bin, Xie Hong, Yang Wenlu. Design of portable ECG signal acquisition circuit [J]. Electronic Design Engineering, 2010, 18(08):123-126.
[3] Duskalov I K, Dotsinsky I A. Developments in ECG acquisition, preprocessing, parameter measurement, and recording[J]. IEEE Engineering in Medicine & Biology Magazine, 1998, 17(2):50-58.
[4] Liang-Hung, Wang, Tsung-Yen, et al. Implementation of a wireless ECG acquisition SoC for IEEE 802.15.4 (ZigBee) applications. [J]. IEEE Journal of Biomedical & Health Informatics, 2015.
[5] Zeng R, Wen D, Su Z, et al. Basic Knowledge of ECG[M]// Graphics-sequenced interpretation of ECG. Springer Singapore, 2016.
[6] Tasaganva M B G, Bhat G V. ECG ACQUISITION SYSTEM[J]. Ersasa Publications.
[7] Gomez-Clapers J, Serrano-Finetti E, Casanella R, et al. Can driven-right-leg circuits increase interference in ECG amplifiers? [C]// Conference: International Conference of the IEEE Engineering in Medicine & Biology Society IEEE Engineering in Medicine & Biology Society Conference. IEEE, 2011.
[8] BACHIR, BENHALA. Ant Colony Optimization for Optimal Low-Pass Butterworth Filter Design[J]. WSEAS Transactions on Circuits and Systems, 2014.
[9] Mckee J J, Evans N E, Wallace D. Sigma-delta analogue-to-digital converters for ECG signal acquisition[C]// International Conference of the IEEE Engineering in Medicine & Biology Society. IEEE, 1996.