

Application Note

Analog Front-End for Electrocardiogram Monitor AN-CM-326

Abstract

This application note describes the design of an analog front-end for an electrocardiography device. The circuit utilizes the commonly used technique of measuring electrical heart activity using three electrodes applied to the arms and legs. These electrodes detect the small electrical signal that results from cardiac muscle contraction (the heartbeat). The unique auto-trim feature of the SLG47004 enables output signal level stabilization in conditions of interference and baseline drift. The application note also contains test results of a hardware prototype.

This application note comes complete with design files which can be found in the References section.

Analog Front-End for Electrocardiogram Monitor

Contents

Abstract	1
Contents	2
Figures	2
1 Terms and Definitions	3
2 References	3
3 ECG Basics and Analog Front-End Requirements	4
4 Top Structure of the Analog Front-End	4
4.1 Typical Human ECG Waveform.....	5
5 SLG47004 Internal Design	5
5.1 Electrical Schematic of Analog Front-End	6
6 Internal Block Configuration	6
6.1 OpAmp0 and OpAmp1 Configurations	6
6.2 Internal OpAmp Configuration	7
6.3 HD Buffer Configuration	7
6.4 Rheostat0 and Rheostat1 Configuration.....	8
6.5 Oscillator Configurations	9
6.6 I ² C Macrocell Configuration	9
6.7 GPIO Configurations.....	9
7 Normal Operation Mode	10
8 Prototype Testing	11
9 Conclusion	12
Revision History	13

Figures

Figure 1: Structure of ECG Analog Front-End	4
Figure 2: Typical ECG of Healthy Heart	5
Figure 3: Design Configuration of SLG47004	5
Figure 4: Electrical Schematic of Analog Front-End	6
Figure 5: Operational Amplifier 0 and 1 Settings	6
Figure 6: Internal OpAmp Settings	7
Figure 7: HD Buffer and OpAmp0 Vref Settings.....	7
Figure 8: Digital Rheostat 0 and 1 Settings.....	8
Figure 9: Oscillator 0 and 1 Settings	9
Figure 10: GPIO Settings	10
Figure 11: Seven Second Heart Waveform (500 mV/div, 500 ms/div).	11
Figure 12: Zoomed Heart Waveform (100 mV/div, 500 ms/div).....	11
Figure 13: Raw Digitized Signal	12
Figure 14: Signal Without 50 Hz Noise	12
Figure 15: Signal After Median Filter.....	12

Analog Front-End for Electrocardiogram Monitor

1 Terms and Definitions

AFE	Analog Front-End
ECG	Electrocardiogram
HR	Heart Rate
IC	Integrated Circuit
OpAmp	Operational Amplifier
INSTAmp	Instrumentation Amplifier

2 References

For related documents and software, please visit:

<https://www.dialog-semiconductor.com/products/greenpak/analog-greenpaks/slg47004>

Download our free [GreenPAK Designer](#) software [1] to open the .gp files [2] and view the proposed circuit design. Use the [GreenPAK development tools](#) [3] to freeze the design into your own customized IC in a matter of minutes. Find out more in a complete library of application notes [4] featuring design examples as well as explanations of features and blocks within the GreenPAK IC.

- [1] [GreenPAK Designer Software](#), Software Download and User Guide
- [2] [AN-CM-326 Analog Front-End for Electrocardiogram Monitor.gp](#), [GreenPAK Design File](#)
- [3] [GreenPAK Development Tools](#), [GreenPAK Development Tools Webpage](#)
- [4] [GreenPAK Application Notes](#), [GreenPAK Application Notes Webpage](#)
- [5] SLG47004, Datasheet
- [6] Filters for ECG digital signal processing / Ondracek O., Jozef P., Elena C. // International Conference "Trends in Biomedical Engineering". - University of Zilina, September 7 - 9, 2005. P. 91-96
- [7] ECG Noise Cancellation Using Digital Filters / Hosseini H., Nazeran H., Reynolds K. // 2nd International Conference on Bioelectromagnetism, 1998. P. 151-152

Author: Svyatoslav Skalsky

Analog Front-End for Electrocardiogram Monitor

3 ECG Basics and Analog Front-End Requirements

An electrocardiogram is a recorded electrical signal resulting from a contraction of heart muscles. It can detect deviation from a normal heartbeat and can be used to diagnose illnesses or optimize a training load. The signal must first be amplified to a level that is suitable for recording (electrodes on the arms can give voltages in the range of tens of microvolts to a millivolt peak-to-peak). The bandwidth of the signal is from 0.05 to 100 Hz. To amplify such a small signal, an amplifier with a gain of around 1000 should be applied. AC interference from the power grid should be canceled out along with DC offsets from the electrodes. As a rule, an instrumentation amplifier with a large common-mode voltage suppression is used. The common mode voltage is then amplified, inverted, and fed into a leg electrode for active interference suppression. Additionally, a low-pass filter, high pass filter, and band suppression filter are applied after amplification.

All electrical connections of the amplifier have to be isolated from mains and from devices supplied from it. It is difficult to construct a power supply with a small amount of stray capacitance to mains, so we will choose a battery-powered device, which will provide a simple solution for a low cost and isolated power source with a minimum amount of stray capacitance.

The SLG47004 can deliver only one instrumentation amplifier, so we will use AC filtering on the digital side. We will use a simple DC reference point for a leg electrode without active interference cancellation.

4 Top Structure of the Analog Front-End

The simplified structural scheme is shown in Figure 1.

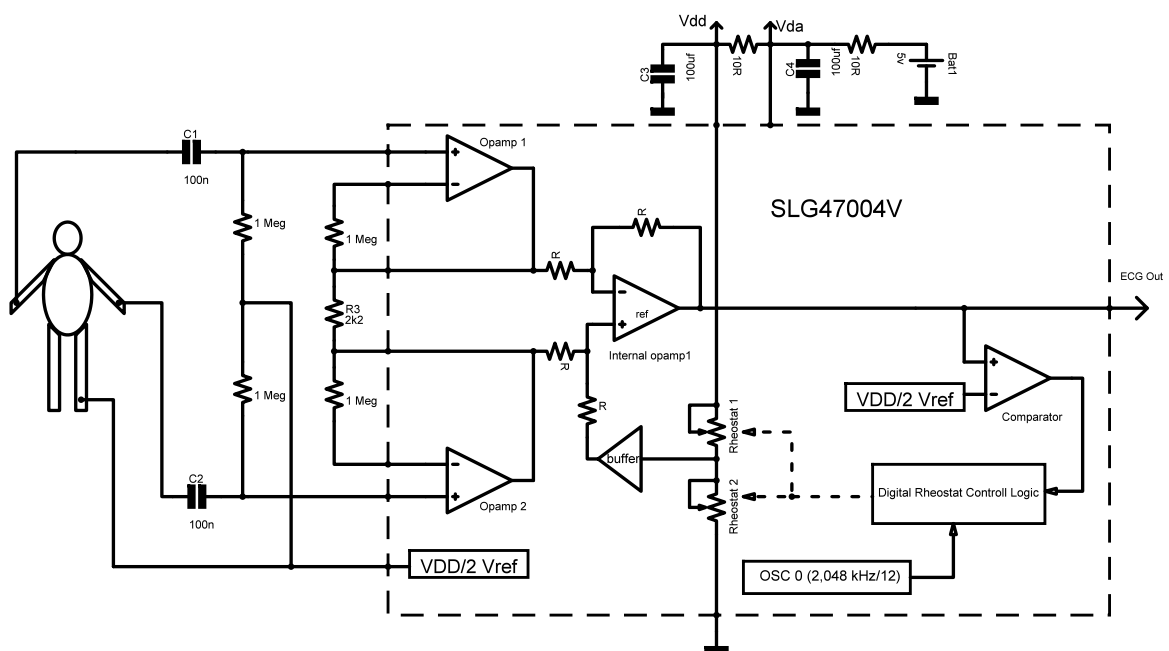


Figure 1: Structure of ECG Analog Front-End

Analog Front-End for Electrocardiogram Monitor

4.1 Typical Human ECG Waveform

A typical electric signal from a heart, picked up by the electrodes on the arms, is shown in Figure 2. The typical ECG waveform has 5 peaks called P-Q-R-S-T. These peaks correspond to the activity of different parts of the heart.

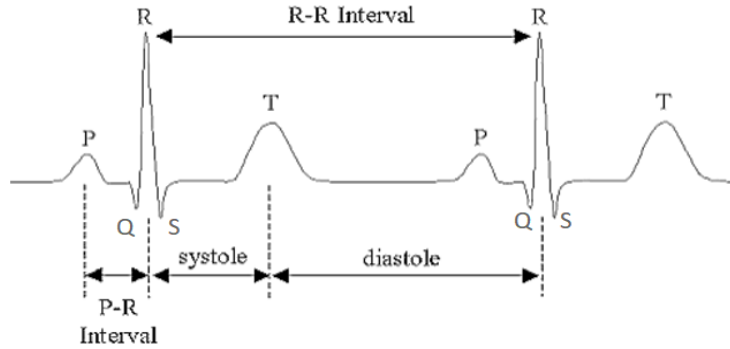


Figure 2: Typical ECG of Healthy Heart

5 SLG47004 Internal Design

The proposed design configuration is shown in Figure 3.

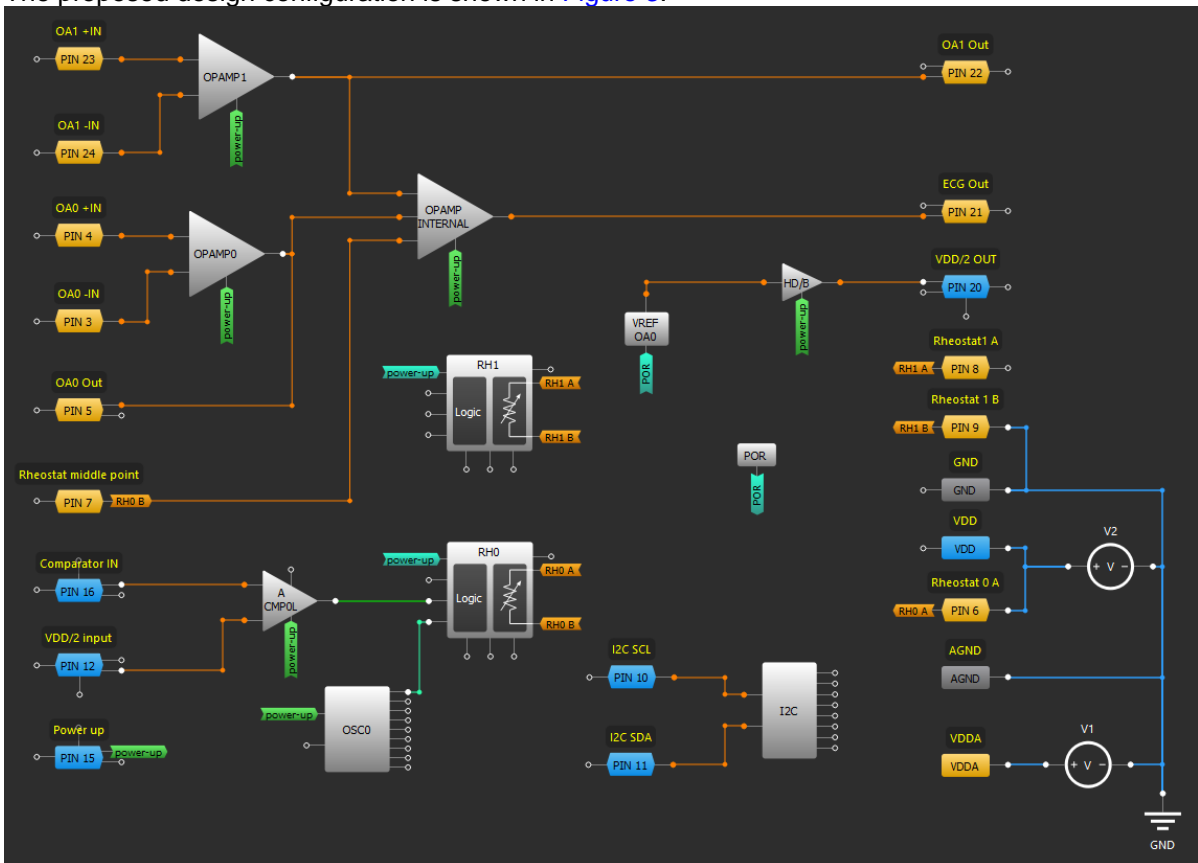


Figure 3: Design Configuration of SLG47004

Analog Front-End for Electrocardiogram Monitor

5.1 Electrical Schematic of Analog Front-End

The electrical schematic of the analog front-end is shown in Figure 4.

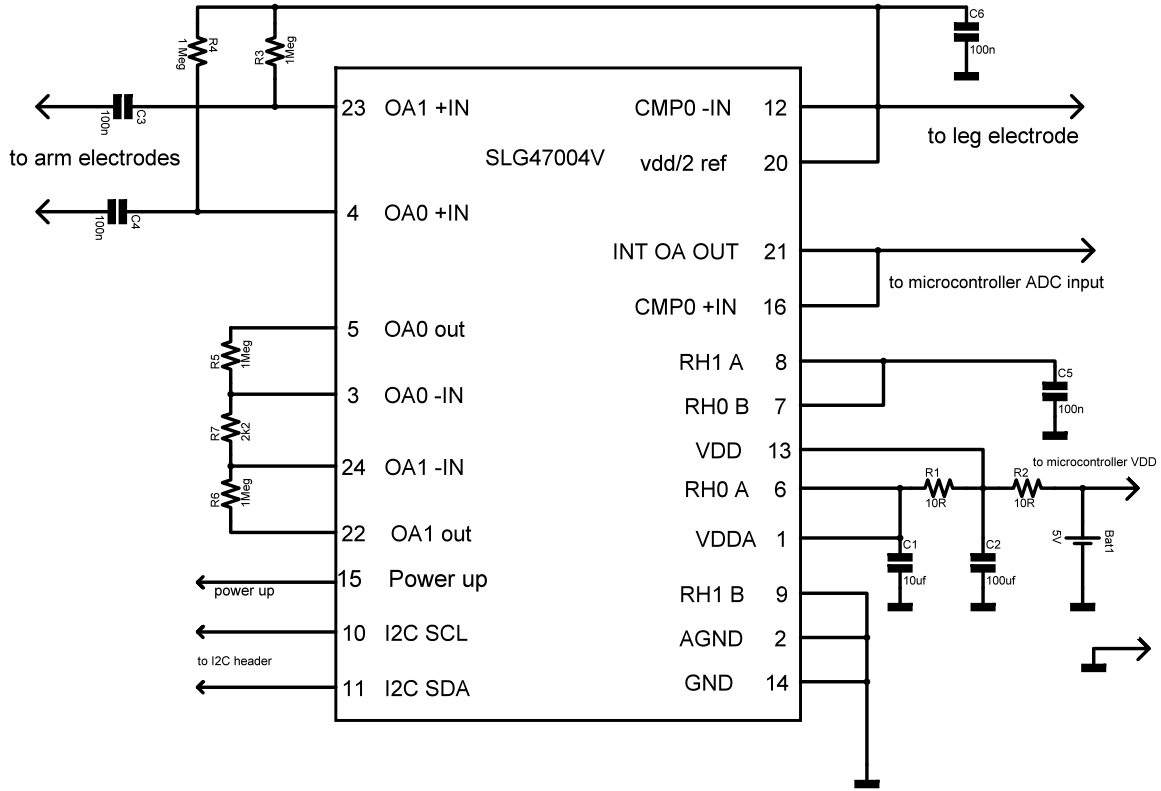


Figure 4: Electrical Schematic of Analog Front-End

6 Internal Block Configuration

6.1 OpAmp0 and OpAmp1 Configurations

OpAmp0 and 1 use the same configuration, shown in Figure 5.

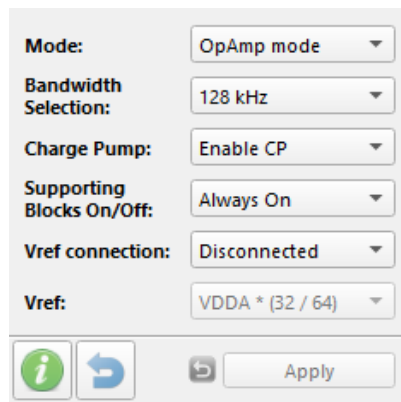


Figure 5: Operational Amplifier 0 and 1 Settings

Analog Front-End for Electrocardiogram Monitor

6.2 Internal OpAmp Configuration

The internal OpAmp configuration is shown in Figure 6.

Figure 6: Internal OpAmp Settings

6.3 HD Buffer Configuration

The HD Buffer shares the voltage reference with OpAmp0. In the current project, the internal Vref is disconnected from OpAmp0. The HD Buffer and OpAmp0 Vref configurations are shown in Figure 7.

Figure 7: HD Buffer and OpAmp0 Vref Settings

Analog Front-End for Electrocardiogram Monitor

6.4 Rheostat0 and Rheostat1 Configuration

The rheostat in this project is configured as a digital potentiometer. Its configuration is shown in Figure 8.

Digital Rheostat0	Digital Rheostat1
Mode: <input type="text" value="None"/>	Mode: <input type="text" value="Potentiometer"/>
Charge Pump Enable: <input type="text" value="Always On"/>	Charge Pump Enable: <input type="text" value="From matrix"/>
Charge Pump Clock: <input type="text" value="OSC1"/>	Charge Pump Clock: <input type="text" value="OSC1"/>
Auto-Trim: <input type="text" value="Disable"/>	Auto-Trim: <input type="text" value="Disable"/>
Active level for UP/DOWN: <input type="text" value="Up when LOW"/>	Active level for UP/DOWN: <input type="text" value="Up when HIGH"/>
Resistance (initial data): <input type="text" value="497"/> <small>(Range: 0 - 1023)</small>	Resistance (initial data): <input type="text" value="526"/> <small>(Range: 0 - 1023)</small>
Connections	Connections
UP/DOWN source: <input type="text" value="Ext. (From matrix)"/>	UP/DOWN source: <input type="text" value="Chopper ACMP"/>
Clock: <input type="text" value="Ext. Clk. (From mat)"/>	Clock: <input type="text" value="From Chopper ACI"/>
<input type="button" value="i"/> <input type="button" value="↶"/> <input type="button" value="↷"/> <input type="button" value="Apply"/>	<input type="button" value="i"/> <input type="button" value="↶"/> <input type="button" value="↷"/> <input type="button" value="Apply"/>

Figure 8: Digital Rheostat 0 and 1 Settings

Analog Front-End for Electrocardiogram Monitor

6.5 Oscillator Configurations

The configurations of Oscillator 0 and 1 are shown in [Figure 9](#).

OSC0		OSC1	
Control pin mode:	Force on	Control pin mode:	Force on
OSC power mode:	Force Power On	OSC power mode:	Force Power On
Clock selector:	OSC	Clock selector:	OSC
'OSC0' frequency:	2.048 kHz	'OSC1' frequency:	2.048 MHz
'CLK' predivider by:	1	'CLK' predivider by:	1
'OUT0' second divider by:	12	'OUT0' second divider by:	1
'OUT1' second divider by:	1	'OUT1' second divider by:	1
Information		Information	
Frequency		Frequency	
Clock output configuration:		Clock output configuration:	
RC OSC Output	Value	RC OSC Output	Value
OUT0	OSC0 Freq. /12	OUT0	OSC1 Freq.
OUT1	OSC0 Freq.	OUT1	OSC1 Freq.
CLK	OSC0 Freq.	CLK	OSC1 Freq.
CLK /8	OSC0 Freq. /8	CLK /8	OSC1 Freq. /8
CLK /64	OSC0 Freq. /64	CLK /64	OSC1 Freq. /64
CLK /512	OSC0 Freq. /512	CLK /512	OSC1 Freq. /512
CLK /4096	OSC0 Freq. /4096		
CLK /32768	OSC0 Freq. /32768		
CLK /262144	OSC0 Freq. /262144		
Apply		Apply	

Figure 9: Oscillator 0 and 1 Settings

6.6 I²C Macrocell Configuration

The I²C macrocell uses default configurations.

6.7 GPIO Configurations

GPIO Pin 17,18,19,10, and 11 have the default configuration.

The remaining GPIO configurations are shown in [Figure 10](#).

Analog Front-End for Electrocardiogram Monitor

PIN 21 (GPIO)	PIN 20 (GPIO6)	PIN 12 (GPIO0)
I/O selection: Analog input/out	I/O selection: Analog input/out	I/O selection: Analog input/out
Input mode: Analog input/out OE = 0	Input mode: Analog input/out OE = 0	Input mode: Analog input/out OE = 0
Output mode: Analog input/out OE = 1	Output mode: Analog input/out OE = 1	Output mode: Analog input/out OE = 1
Resistor: Floating	Resistor: Floating	Resistor: Floating
Resistor value: Floating	Resistor value: Floating	Resistor value: Floating
PIN 16 (GPIO2)	PIN 15 (GPIO1)	
I/O selection: Analog input/out	I/O selection: Digital input	
Input mode: Analog input/out OE = 0	Input mode: Digital in without OE = 0	
Output mode: Analog input/out OE = 1	Output mode: None OE = 1	
Resistor: Floating	Resistor: Pull Up	
Resistor value: Floating	Resistor value: 100K	

Figure 10: GPIO Settings

7 Normal Operation Mode

Power up Pin 15 has a 100kΩ pull-up resistor, and if left floating will by default power up the oscillator, all three op amps, and the rheostat. When Pin 15 is pulled down by external components, all internal blocks shut off and the SLG47004 goes into power saving mode.

Electrodes on the skin and body have a very high impedance, so common-mode AC power interference is accepted by the electrodes.

Instrumentation amplifiers are good at rejecting common-mode signals, and they also have high-impedance inputs, which are needed for amplification of the very small signal produced by heart muscles in the noisy environment. AC signals from arm electrodes go to an RC high-pass filter (R3, R4, C3, and C4 in Figure 4) with a low cut-off frequency, which eliminates a DC offset that might be present at the input due to the electrochemical processes between the electrode, conductive paste, and the skin. An even DC bias of VDD/2 is introduced to both of the op amp inputs to shift the operation point of the op amp, preventing it from going beyond rails. The voltage divider from R6, R7, and R5 (in Figure 4) forms an external negative feedback loop for an instrumentation amplifier from three op amps in the SLG47004 and has a gain of 910.

The Internal op amp has four resistors with the same value, forming a differential amplifier with a gain of 1.

Op amps have an input offset voltage. In our case, the SLG47004 has a max 1000 uV input offset voltage. This will be amplified by a factor of 910 and can produce up to 1 V of output voltage offset and reduce headroom for our signal, clipping it to GND or VCC (keep in mind that VCC is only 5 V).

To compensate for that error, an auto-trim circuit with digital potentiometer is used. This uses an analog comparator to switch the direction of the digital potentiometer change (up/down), which is clocked by the oscillator.

We are using slow tuning of the instrumentation amplifier reference point to cancel out op amp offset voltages. Multiplied by a large gain factor, they will overload the amplifier output without compensation. A slow floating offset voltage presented by muscle shaking, somatic tremor, or

Analog Front-End for Electrocardiogram Monitor

galvanic contact of electrode metals to the skin are all sources of interference that must be canceled out. The entire circuit of the comparator, reference voltage, potentiometers, and a clock signal slowly adjust an average DC level of the amplifier to a reference voltage level, which is set to $V_{DD}/2$. The rate at which the voltage at the potentiometer output is changing is proportional to a clock frequency, fed into a potentiometer block. Assuming the potentiometer has 1023 steps and is connected to a supply voltage of 5 V, and has a clock of 170 Hz, the auto-trim control loop will have a slew rate of 0.83 V/s. It will also act as a high pass filter with a very low frequency cut-off.

We must consider the error presented by the constant auto-trim process, but in most use cases this is negligible and can be tolerated. If it is undesirable, it can be configured to be switched off after a trimming period using the internal SLG47004 logic.

A reference point of $V_{DD}/2$ potential is fed into the leg electrode, which also becomes present at both sides of capacitors C3 and C4, preventing them from charging (so you don't have to wait until the output signal settles due to the input capacitors' charging time).

8 Prototype Testing

Figure 11 and Figure 12: show the waveform at the analog output of the SLG47004. The raw analog output signal has a high level of 50 Hz noise. Such measurements can't be analyzed, and this is a typical problem for electrocardiography. That's why additional filtering should be applied to the signal.

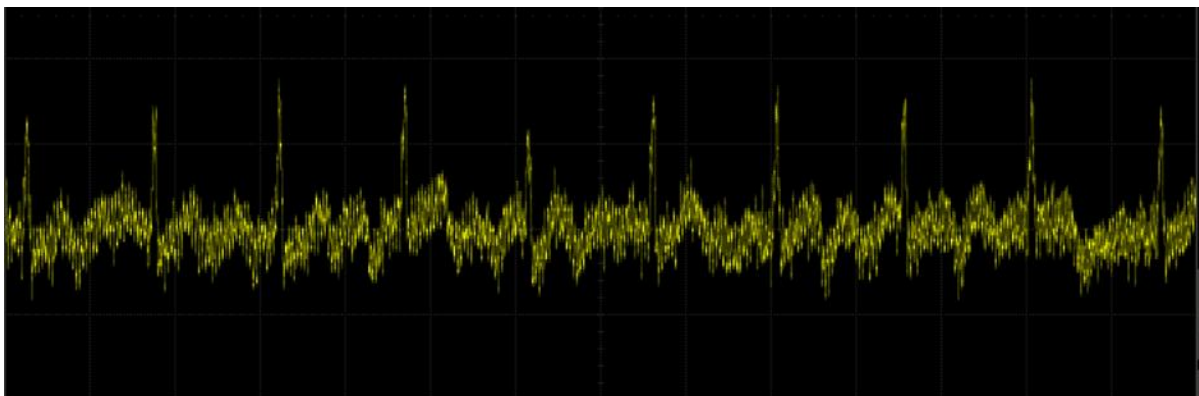


Figure 11: Seven Second Heart Waveform (500 mV/div, 500 ms/div).

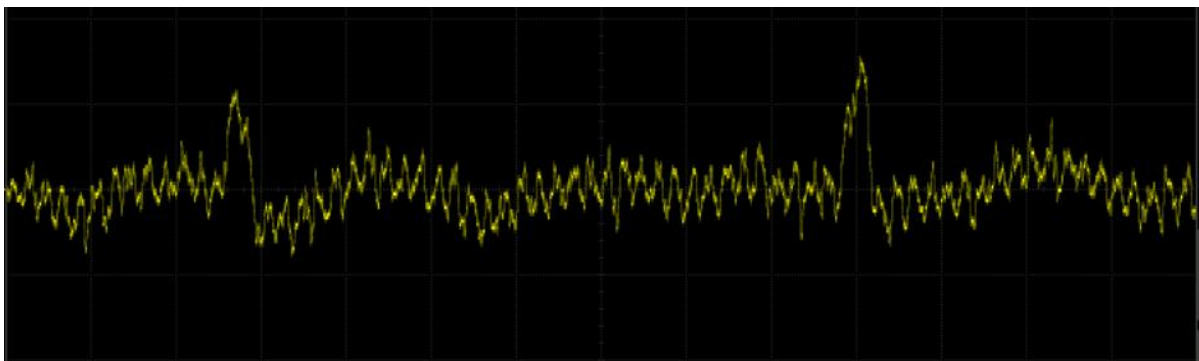


Figure 12: Zoomed Heart Waveform (100 mV/div, 500 ms/div).

The common approach is to apply digital filters to remove power grid noise as well as other noise components [2]. There are many articles that describe and compare different digital filtering approaches [2,3]. Since the purpose of this application note is to show the performance of the analog front-end, we will skip the digital filter synthesis procedure and show the filtered signal.

Analog Front-End for Electrocardiogram Monitor

Figure 13 shows the raw digitized signal. At the 1st filtering stage 50 Hz noise was removed (Figure 14). At the 2nd filtering stage a median filter was applied to the signal (Figure 15).

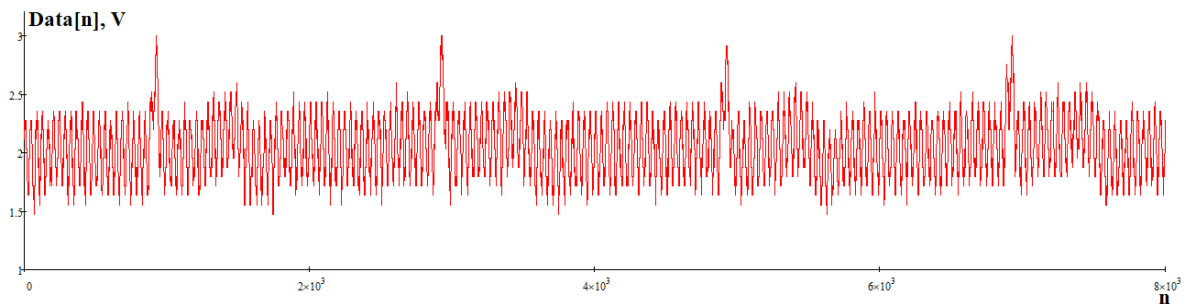


Figure 13: Raw Digitized Signal

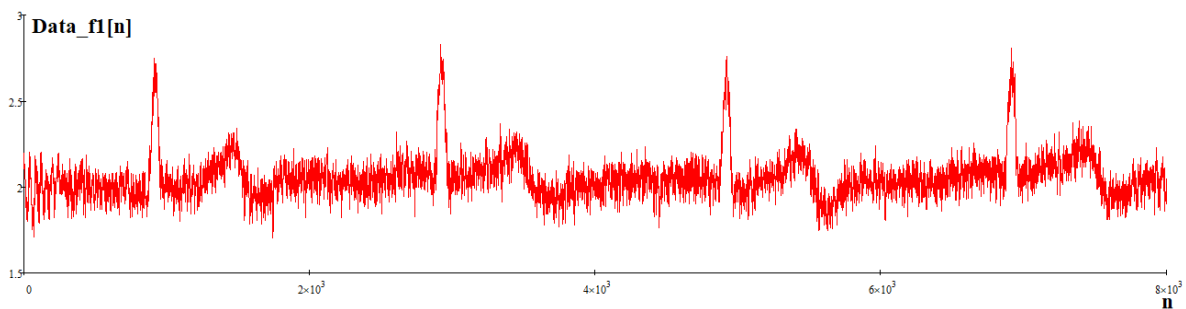


Figure 14: Signal Without 50 Hz Noise

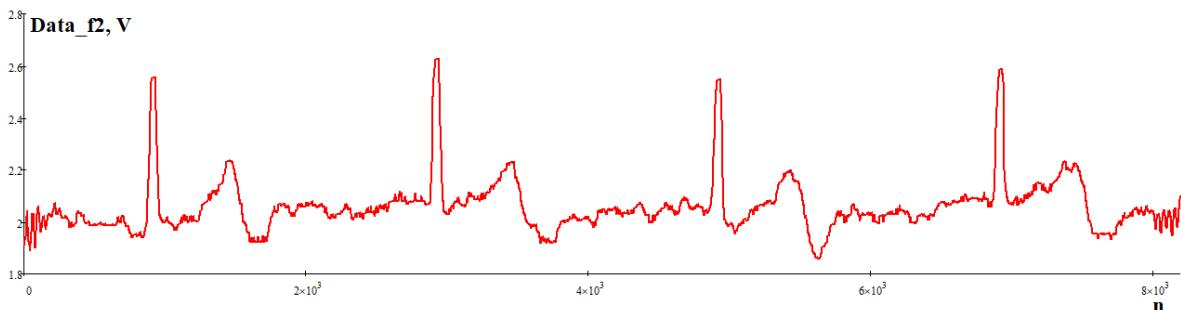


Figure 15: Signal After Median Filter

9 Conclusion

The SLG47004 can be used as a cost-effective integrated solution for the analog front-end of an electrocardiogram monitor. Its unique auto-trim feature allows it to cancel system offset as well as to provide steady output. The embedded instrumentation amplifier provides a good common mode interference rejection, the magnitude of which is much bigger than the signal itself.

Analog Front-End for Electrocardiogram Monitor

Revision History

Revision	Date	Description
1.0	08-Oct-2021	Initial version.

IMPORTANT NOTICE AND DISCLAIMER

RENESAS ELECTRONICS CORPORATION AND ITS SUBSIDIARIES (“RENESAS”) PROVIDES TECHNICAL SPECIFICATIONS AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for developers skilled in the art designing with Renesas products. You are solely responsible for (1) selecting the appropriate products for your application, (2) designing, validating, and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. Renesas grants you permission to use these resources only for development of an application that uses Renesas products. Other reproduction or use of these resources is strictly prohibited. No license is granted to any other Renesas intellectual property or to any third party intellectual property. Renesas disclaims responsibility for, and you will fully indemnify Renesas and its representatives against, any claims, damages, costs, losses, or liabilities arising out of your use of these resources. Renesas' products are provided only subject to Renesas' Terms and Conditions of Sale or other applicable terms agreed to in writing. No use of any Renesas resources expands or otherwise alters any applicable warranties or warranty disclaimers for these products.

(Disclaimer Rev.1.0 Mar 2020)

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
www.renesas.com/contact/

Trademarks

Renesas and the Renesas logo are trademarks of Renesas Electronics Corporation. All trademarks and registered trademarks are the property of their respective owners.