Medical Stethoscope Design Reference Manual

Document Number: DRM132
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Chapter 1
About This Document

1.1 Preface

The purpose of this manual is to specify the features of the Medical Stethoscope (MED-STETH) reference design. It contains descriptions of the hardware incorporated in the Tower System, and the embedded software developed along with the schematic and flow diagrams in each section. The characteristics of microcontrollers, block diagrams, and bill of materials are detailed in this document.

1.2 Audience

This document is intended primarily for software application developers who are considering using the Freescale Tower System and/or the K53 microcontroller in an electronics solution.

Chapter 2
Introduction

2.1 Intended functionality

MED-STETH is an implementation based on the Freescale Tower System and the K53 microcontroller. It provides a GUI to show real-time measurements of the heart rate and the sound frequency, and converts the movements within the body into sounds.

2.2 MED-STETH fundamentals

The main basis of the MED-STETH system is the Doppler effect, which determines the velocity of an object by the change in the frequency of a wave because of its relative movement to an observer. In this particular case, the signal is transmitted by the 3 MHz Doppler probe; however when it bounces on the heart and reaches the probe again, it creates an effect relative to the probe as observer, that perceives as if the original signal was transmitted by the heart toward the probe, so that the source is moving toward the observer and away from it constantly.

2.2.1 The Doppler effect

The Doppler effect is the change in frequency of a wave received by an observer that is moving relative to the source of the transmitted wave.

This change in frequency of the wave can be distinguished if the frequency perceived by the observer when the source is coming towards it is compared with the frequency perceived when the source moves away. If the source is approaching the observer, it perceives that each successive wave crest is emitted from a position closer than the previous one, and takes less time for each crest to reach the observer. Thus, the time interval between the arrival of successive wave crests at the observer is shorter and consequently, the perceived frequency increases. Similarly, if the source is moving away from the observer, the perceived frequency is reduced.

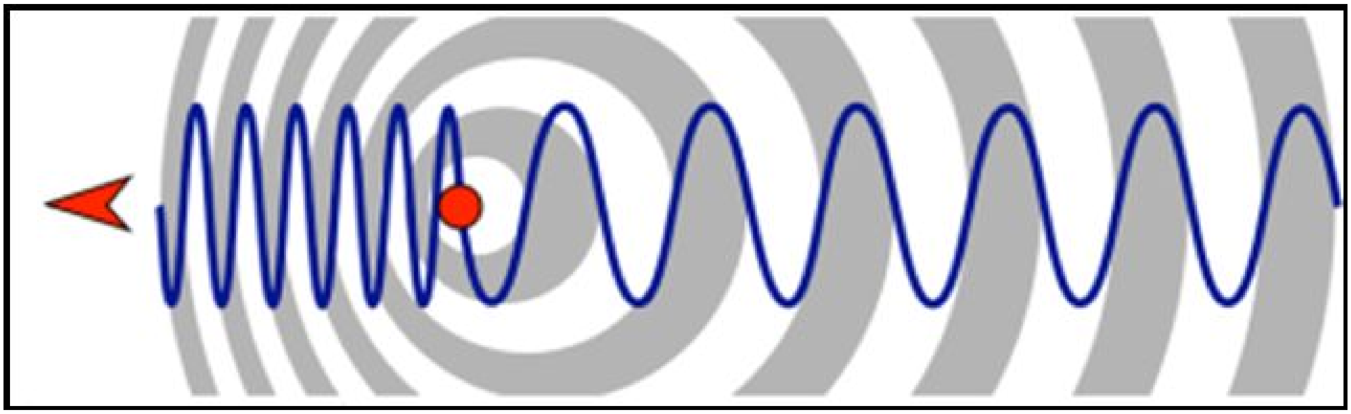


Figure 2-1. Doppler effect representation

2.2.2 Processing the signal

The signal processing starts when the Doppler probe transmits a 3 MHz signal to the heart and then demodulates changes in frequency to obtain the sound of the moving object. The signal is rectified and filtered using a digital bandpass filter to obtain the enveloping wave. Beats per minute (BPM) is calculated with the help of a pulse detection algorithm, taking into account the amplitude and the frequency.

2.3 Solution benefits

The MED-STETH reference design offers a complete solution for the heartbeat detection and measurement of a fetus heart rate. However, the importance of this reference design implementation lies in the way the Freescale tools were used to generate a real healthcare solution.

The elements of this reference design can be referred for subsequent developments as a Fetal Heart Rate Monitor or a Digital Stethoscope.

Every part of hardware and software implemented in this system can be reused or upgraded by future developers interested in the tools provided by Freescale Semiconductor Inc. One of the major benefits of this design is that the developers can improve upon their own implementations or make their development processes shorter, based on the references of the developed modules of this MED-STETH.

Chapter 3
Hardware Design

3.1 Hardware overview

The MED-STETH board is an analog front end which works together through the medical connector with Freescale's TWR-K53 board. It is designed to work with the internal operational amplifiers (OPAMPs) embedded in this MCU. These OPAMPs offer the required signal instrumentation for the probe signal to be filtered and amplified.

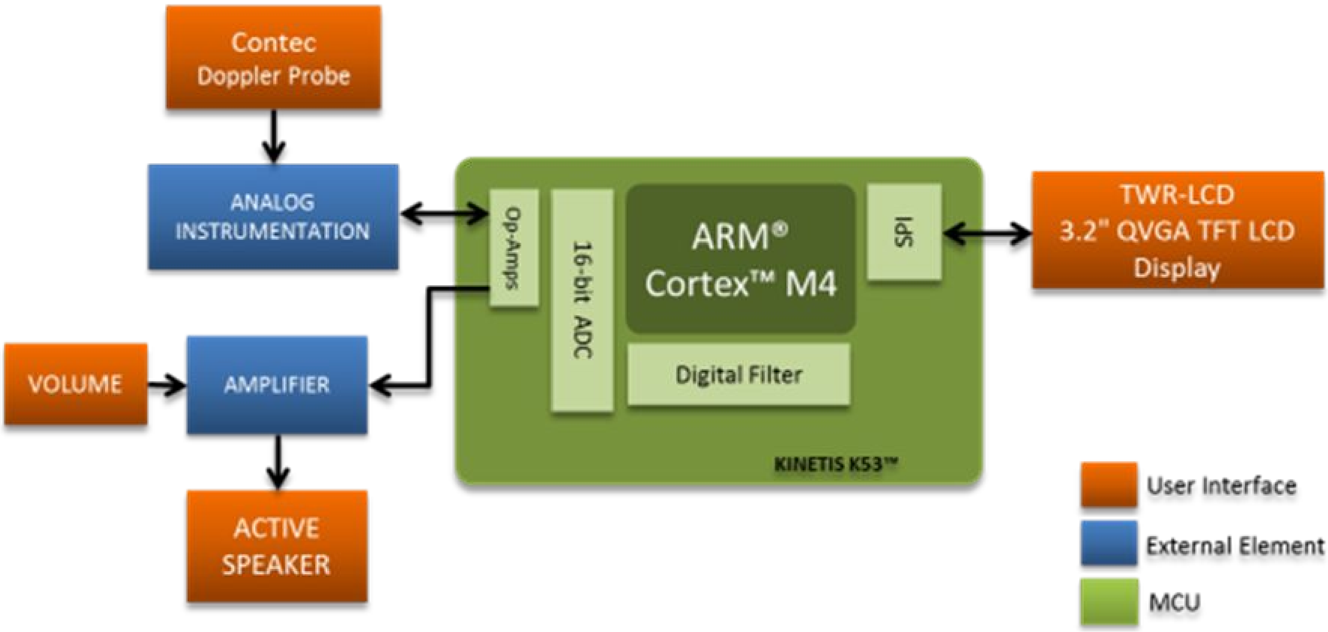


Figure 3-1. Demo general block diagram

3.2 Schematic details

Figure 3-2 depicts the nets of the MED-STETH header connector that links to the TWR boards. As seen in Figure 3-2, only the OPAMP module of the MCU, and the power nets are connected to inputs and outputs of the MED-STETH. The ADC channel reads internally from the OPAMP module for better signal processing.

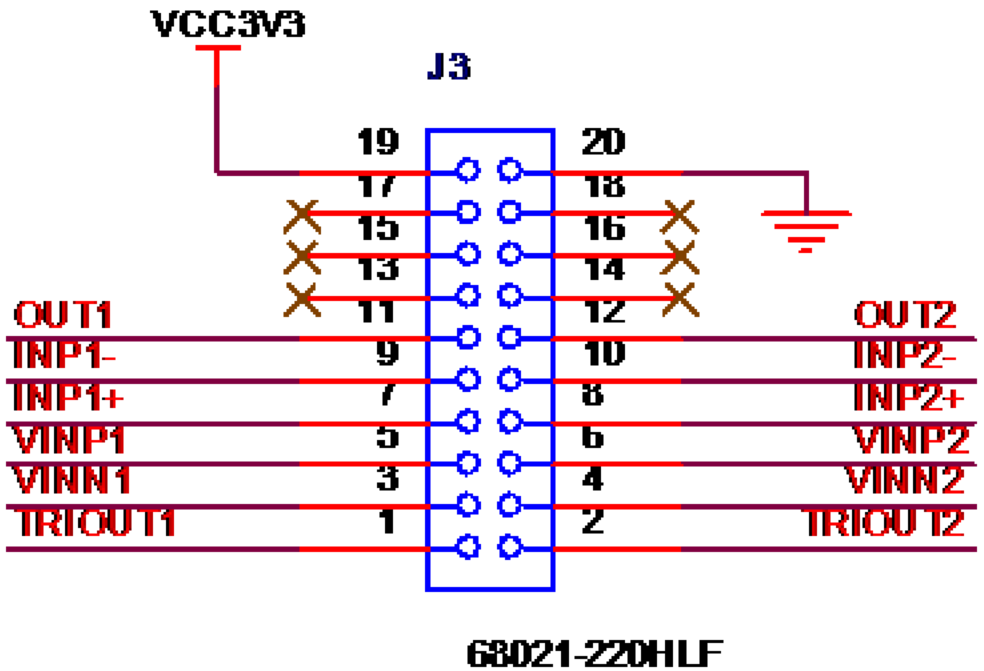


Figure 3-2. Medical connector

The MED-STETH acquires and decouples the power from the main board of the tower system. The net VCC3V3 seen in Figure 3-3 is the digital power source coming from the tower. Then, capacitors and ferrite beads set to decouple and generate the analog power that will run the MED-STETH. The LED D1 (Figure 3-3) will turn on when the board is powered.

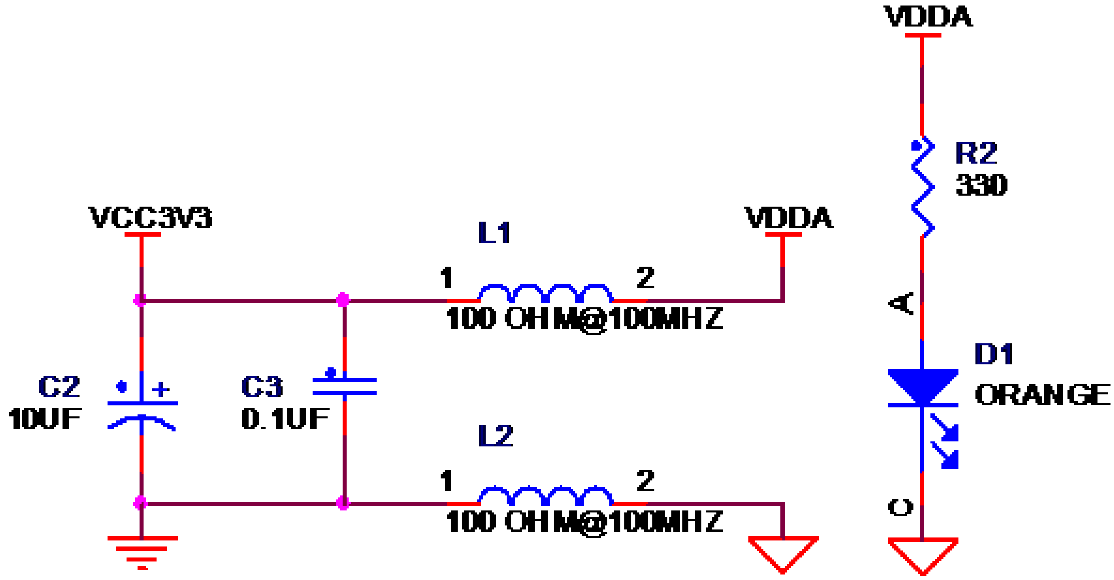


Figure 3-3. Power stage

Figure 3-4 shows the configuration used to generate the Vref for the analog instrumentation. A capacitor is used for filtering high-frequency noise.

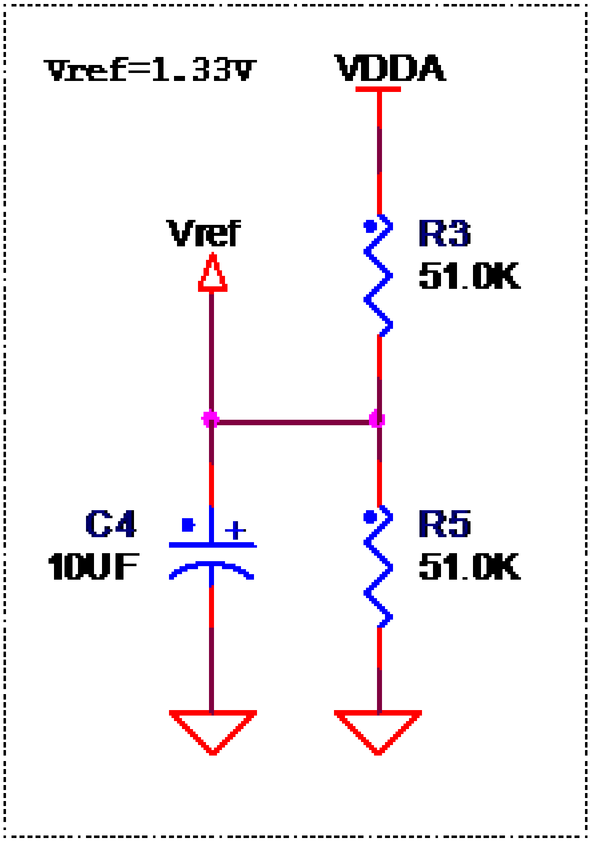


Figure 3-4. Vref stage

The Doppler probe used for this project uses a USB port to communicate with the rest of the circuit, but doesn't support USB communication protocol. The configuration of the probe is shown in Figure 3-5. The probe delivers the demodulated signal through pin #2 of the USB connector, and then a high-pass filter eliminates the DC component and raises it to Vref.

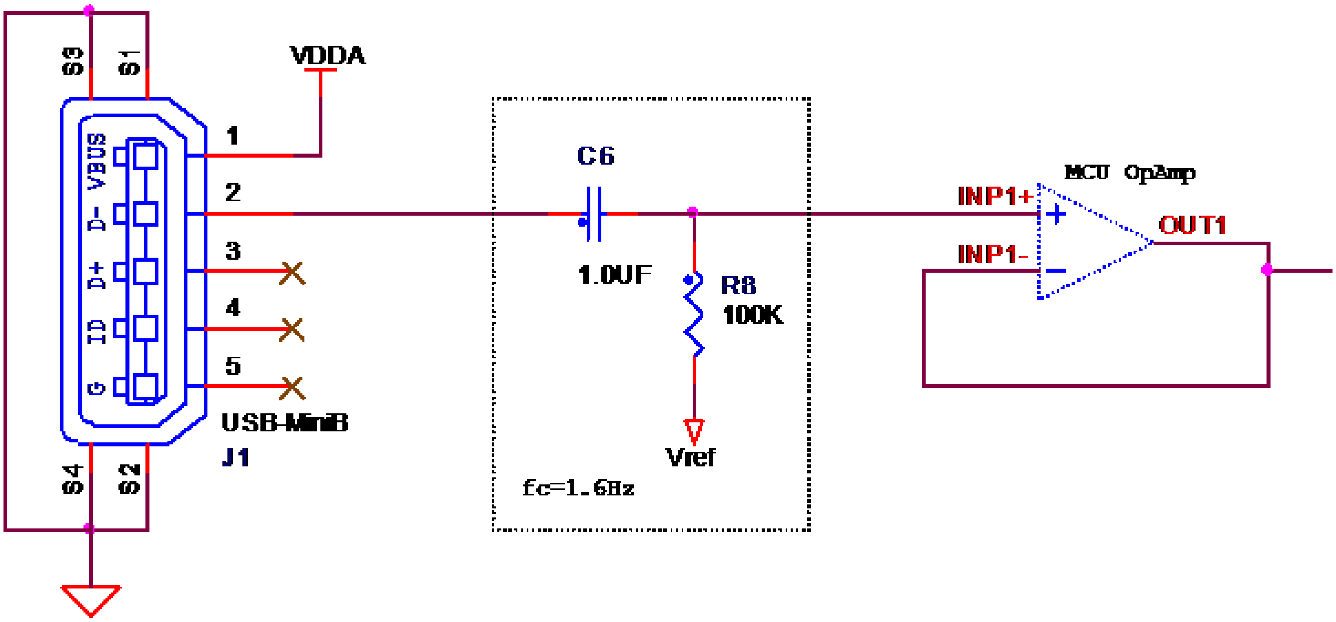


Figure 3-5. Transceiver signal aquisition

Before amplifying the Doppler signal, it is put through the first OPAMP, which is configured as a voltage follower, as shown in Figure 3-6. The OPAMP acts as a buffer, giving the correct amount of power required for the amplification process.

The signal is then filtered and amplified through a simple active bandpass filter shown in Figure 3-6. The lower cuttoff frequency is set to 16 Hz and the higher to 3.5 kHz. This configuration is set on the first transimpedance amplifier (TRIAMP) of the MCU.

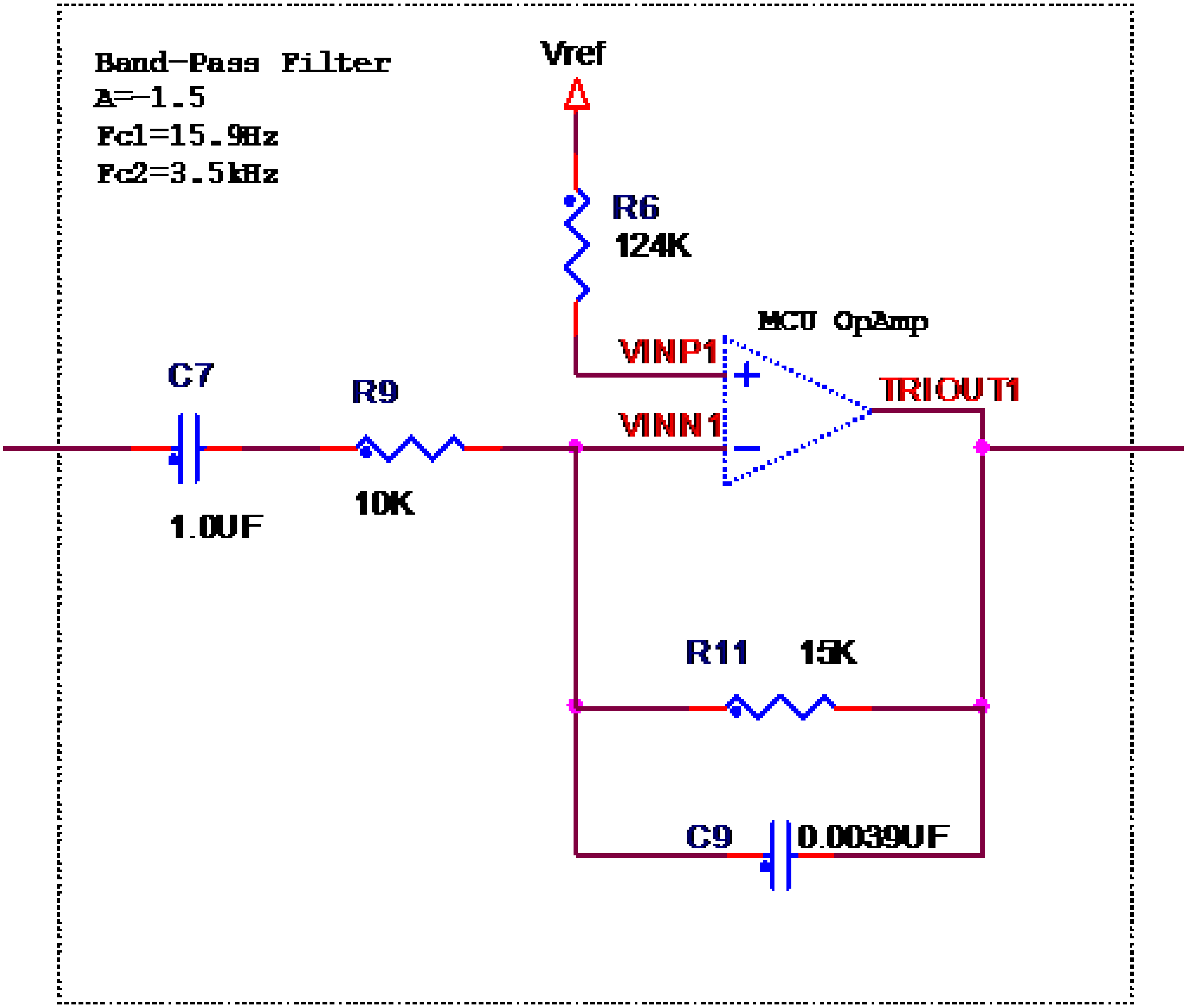


Figure 3-6. First bandpass filter

A second active bandpass filter with the same configuration is implemented. This amplifier has the same cutoff frequencies as the previous TRIAMP. Figure 3-7 illustrates this configuration. Both of these TRIAMPS are externally configurable to be used as general-purpose OPAMPs.

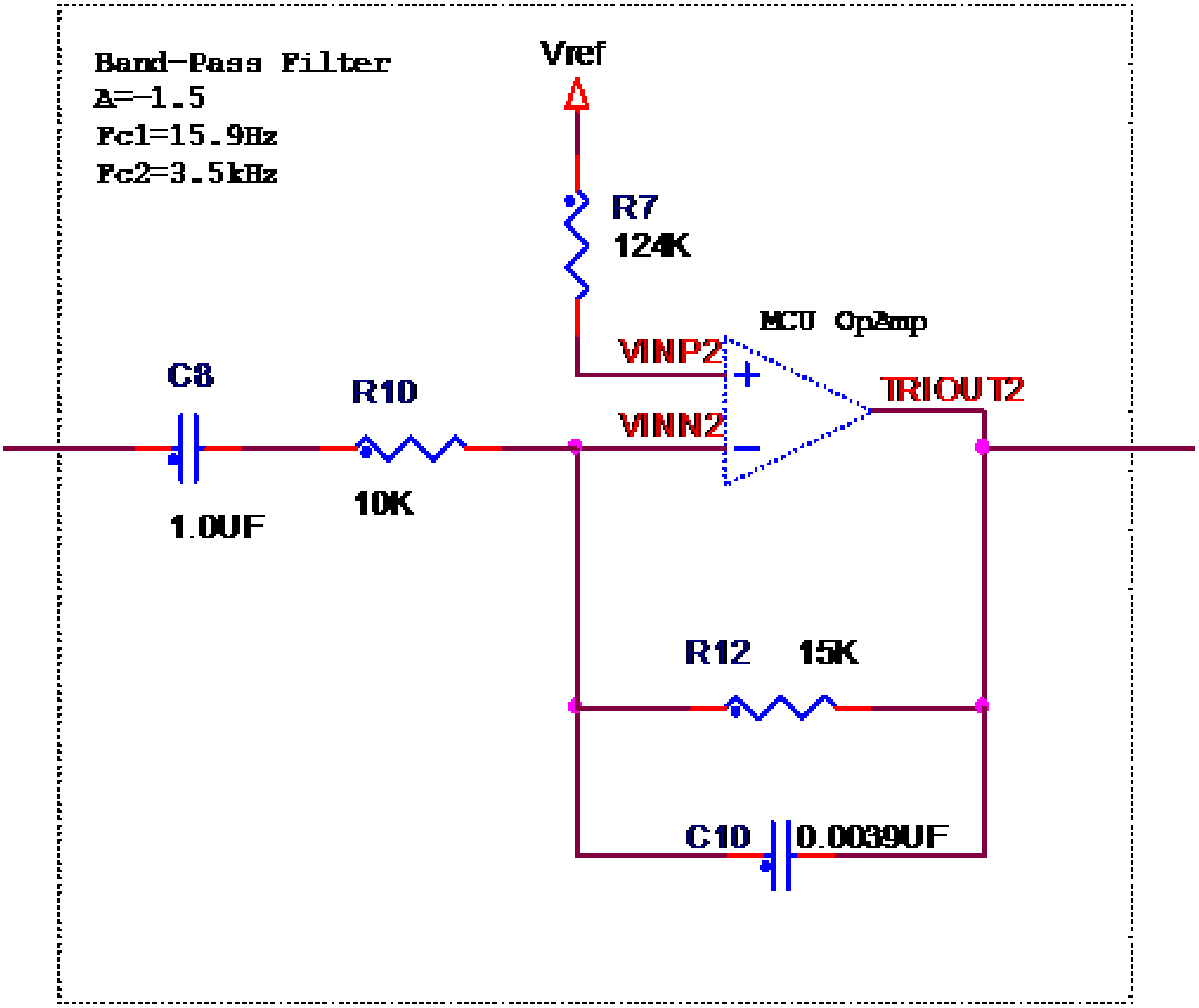


Figure 3-7. Second bandpass filter

The last OPAMP is configured as a non-inverting amplifier with a variable gain. This helps to adjust the amplitude of the signal for the correct analysis and detection of pulses to calculate the BPM. Figure 3-8 illustrates this configuration.

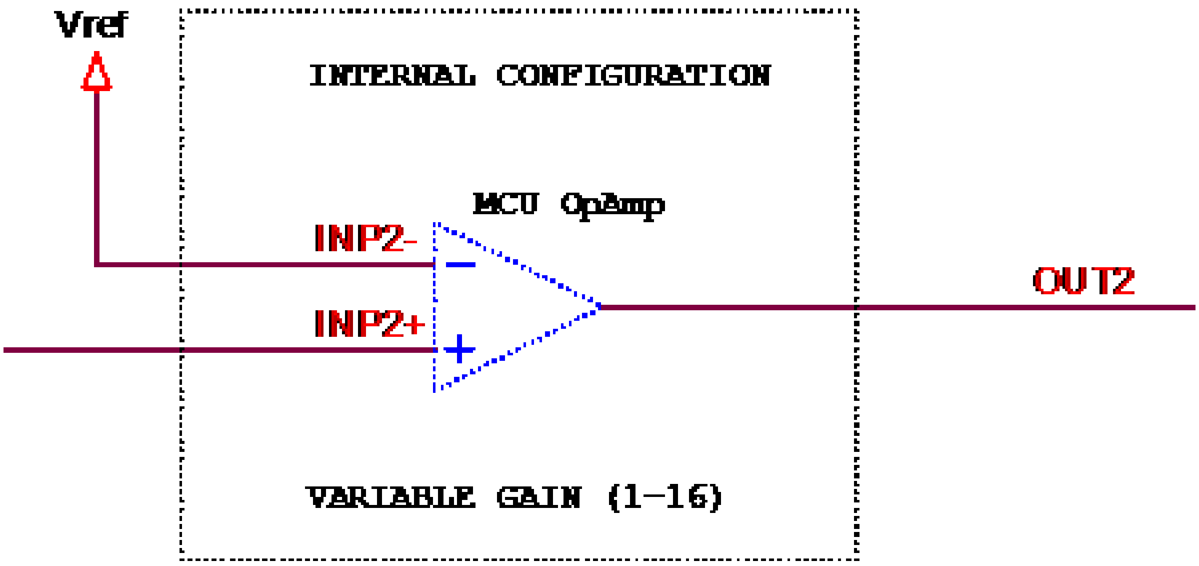


Figure 3-8. Variable gain amplifier

After the last amplification stage, the signal is read from the ADC and is digitally processed. The 3 W audio power amplifier circuit shown in Figure 3-9, picks up this signal and helps drive the sound for the external speaker.

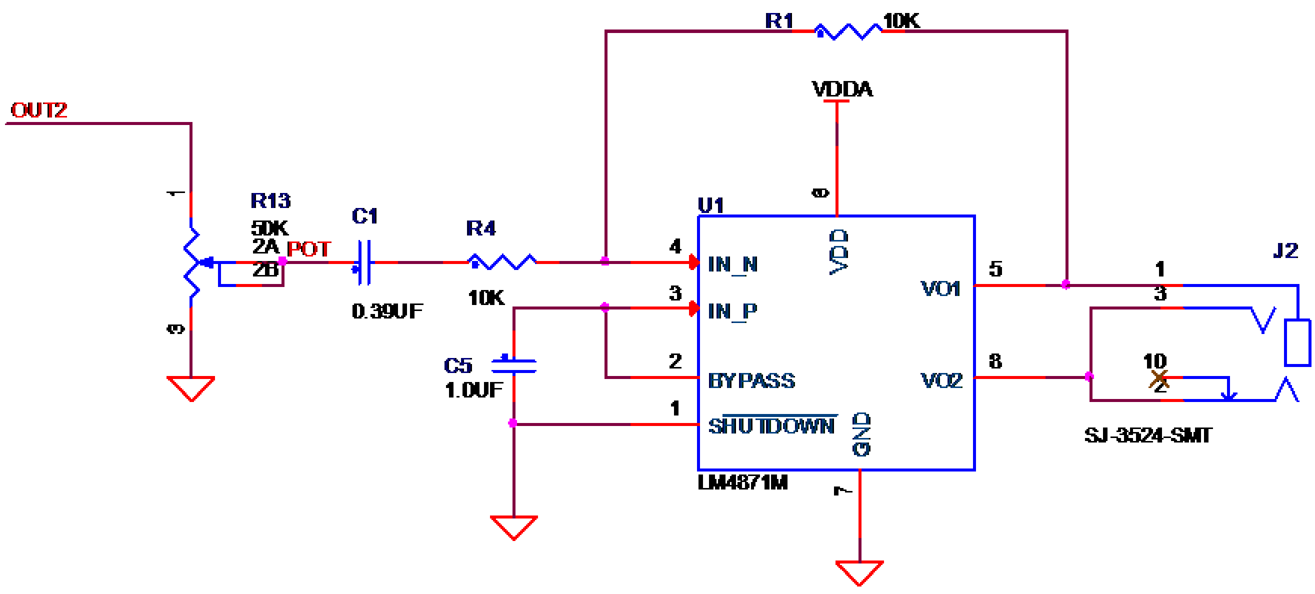


Figure 3-9. Audio power amplifier

This amplification circuit will work only with active speakers. If a passive speaker is chosen instead, the voltage of the probe and the amplifier will need to be isolated. This could be achieved by a DC-DC isolated converter.

An alternative to a potentiometer replacement can be selected before assembling the board (Figure 3-10).

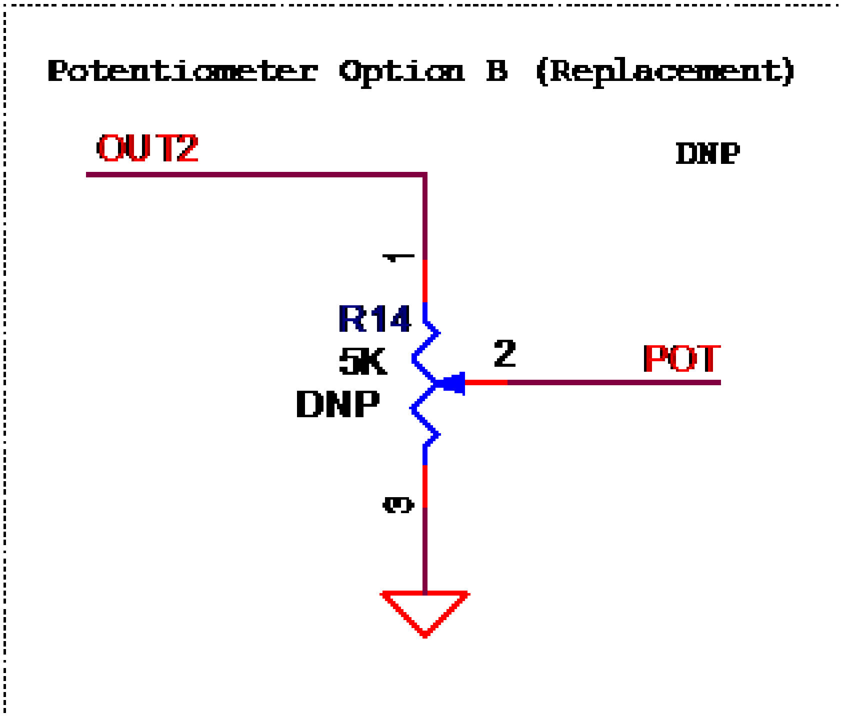


Figure 3-10. Potentiometer replacement

3.3 PCB layout details

This section outlines the hardware design considerations for the printed circuit board (PCB) of the MED-STETH reference design. This section will describe the stackup selected, and would provide a quick description of each layer and location of the principal modules.

PCB stackup is a very important factor in determining the EMC performance of a device. A good stackup among other things, is a very effective way of reducing radiation from the PCB. Figure 3-11 is the stackup selected for the activity monitor.

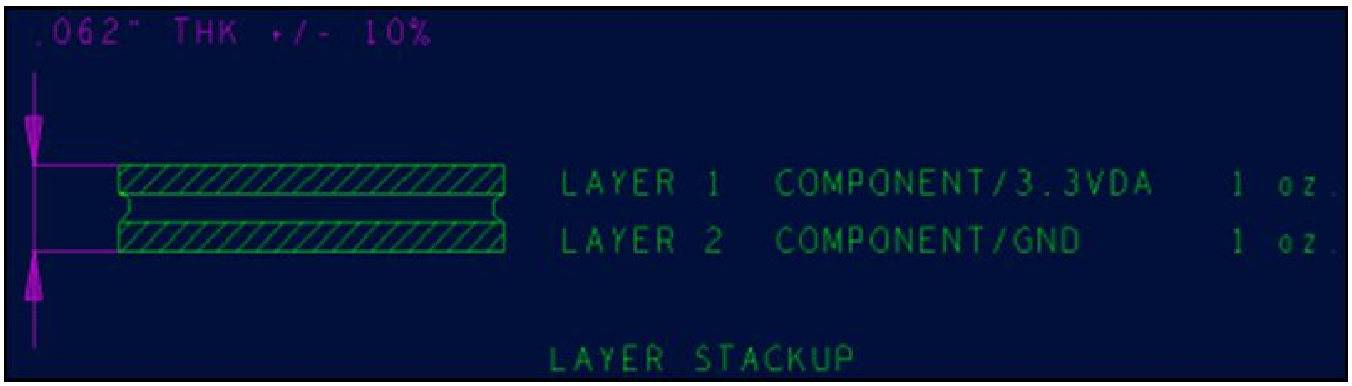


Figure 3-11. Layer stackup

Figure 3-12 shows the top and bottom view of component placement in a MED-STETH PCB. The resistors and capacitors used in the analog instrumentation module are placed as close to the header, as possible.

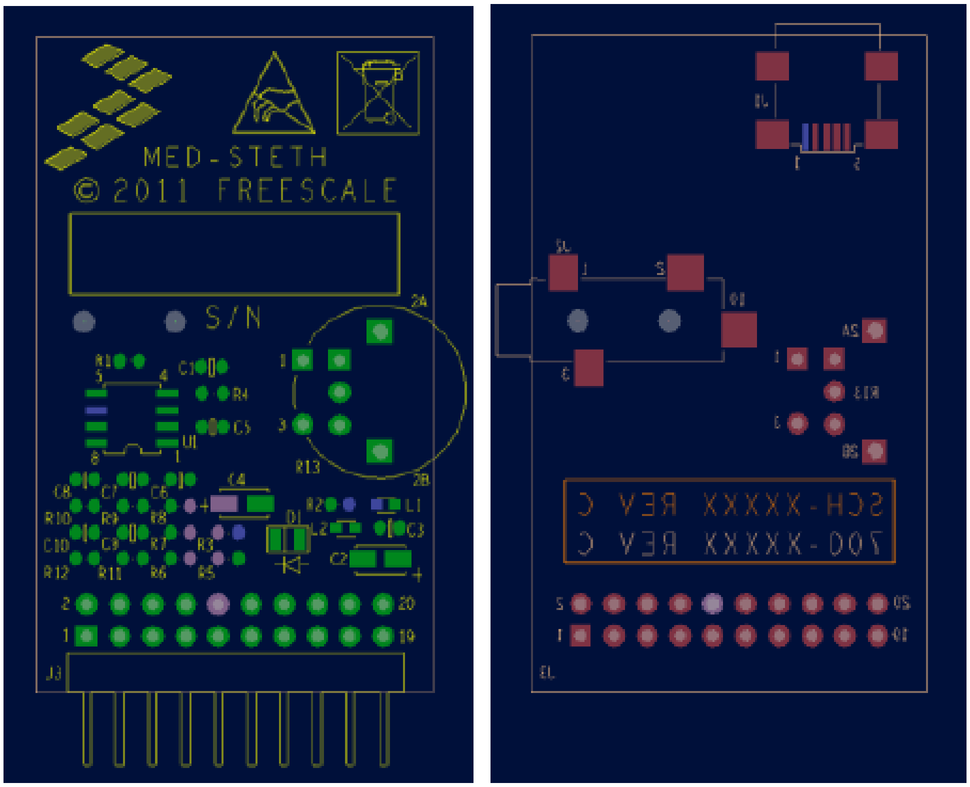


Figure 3-12. MED-STETH top and bottom layers

The connectors and potentiometer are placed so that they are easily accessible by the users. Figure 3-13 shows the top and bottom layers of the MED-STETH PCB. The top layer has a 3.3 V pour and the bottom layer has a ground pour.

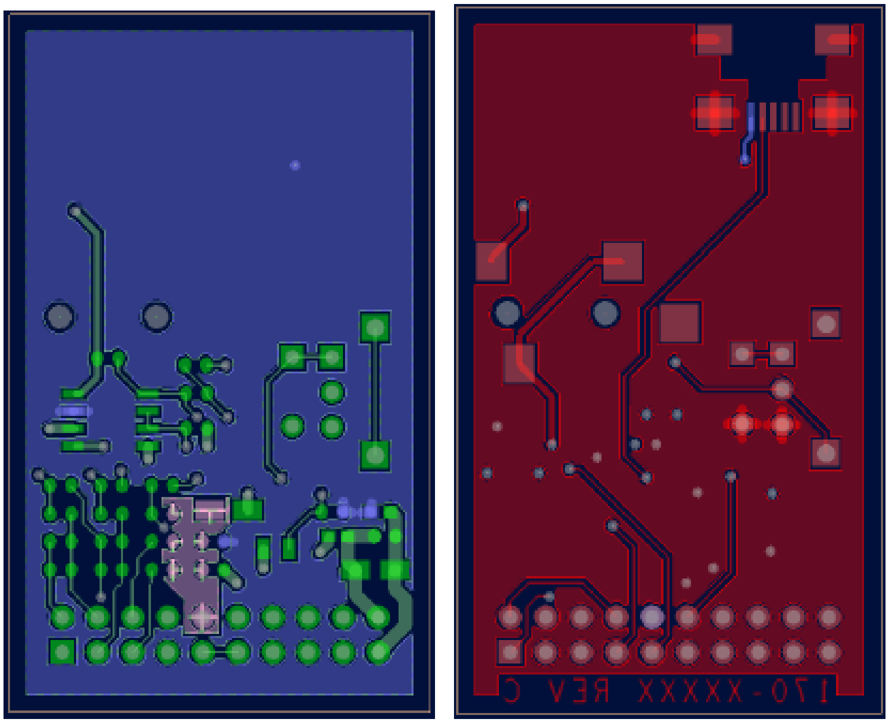


Figure 3-13. MED-STETH power and ground layers

Figure 3-14 depicts the top and bottom view of the fully-assembled MED-STETH PCB. The main parts and modules are labeled in the following figure.

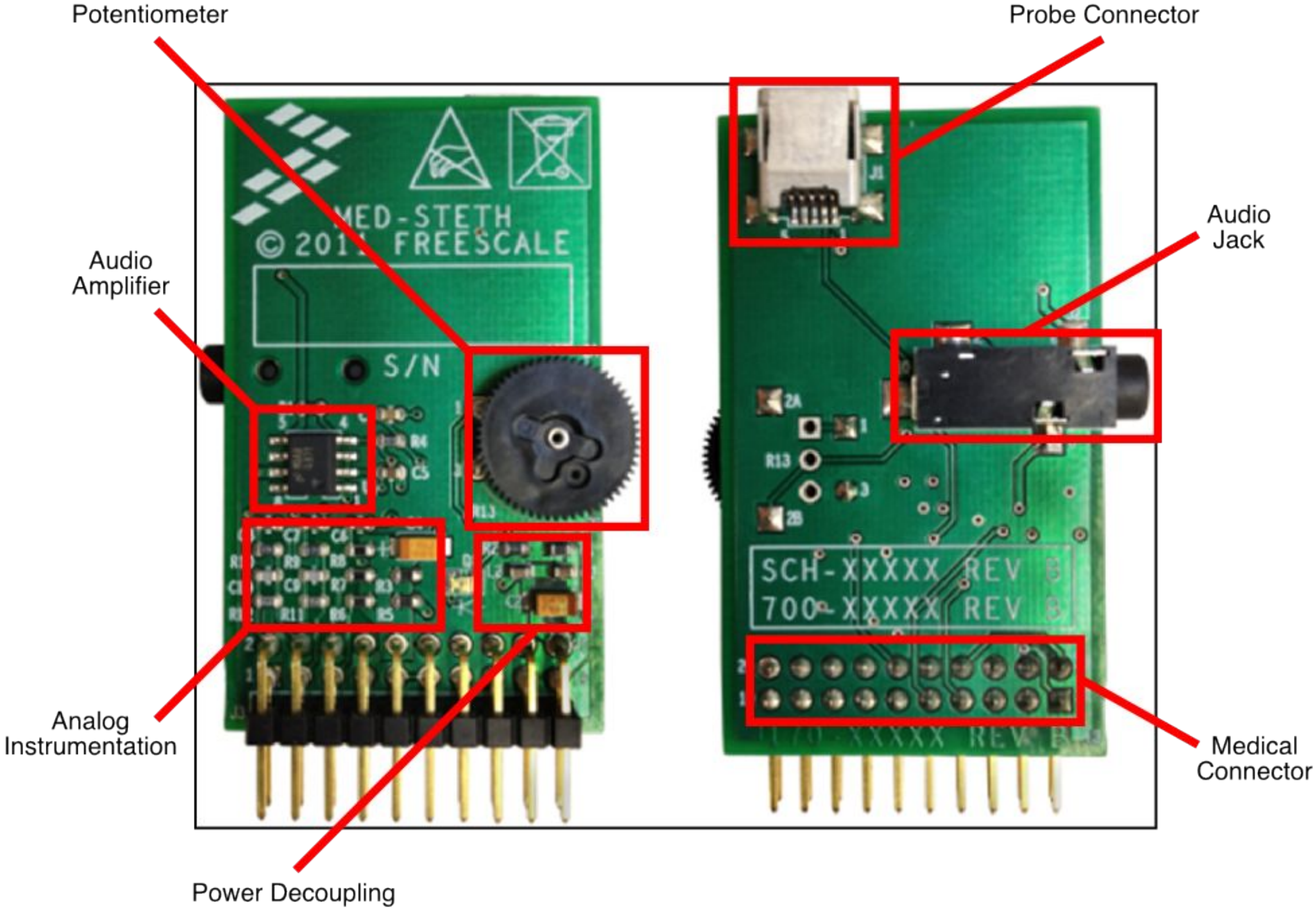


Figure 3-14. MED-STETH top and bottom assembly

Chapter 4
Software Design

4.1 Software overview

In this chapter, the main software functionalities and the program flow are explained. The following flowchart explains the sequence of the processes of the MED-STETH program running in the K53 MCU.

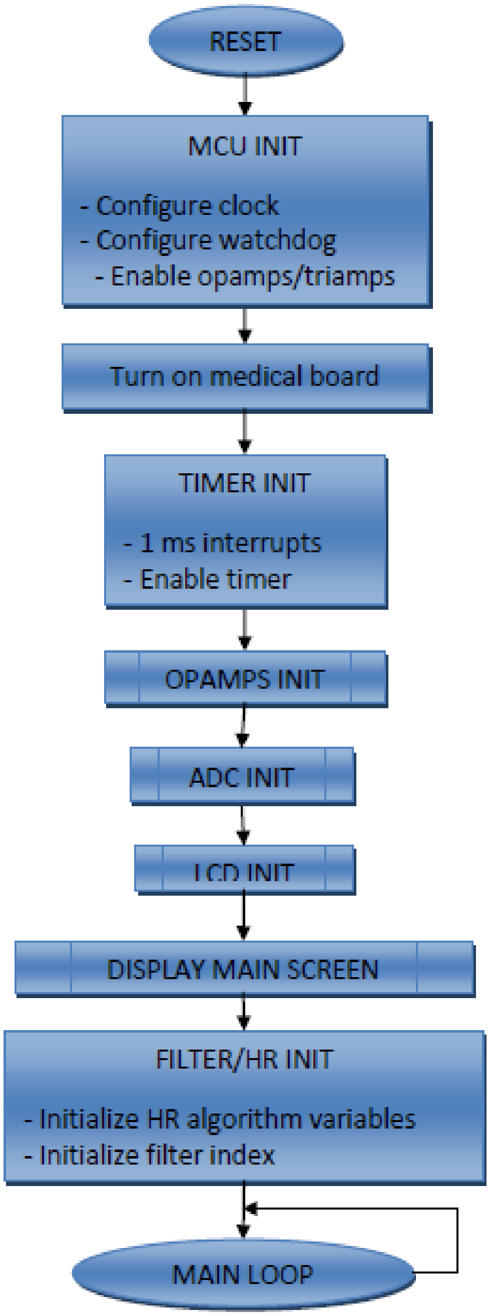


Figure 4-1. Main flow diagram

The first sequence after the Reset or Boot indicator, represents the initialization process. Such a process includes initializing the MCU, timer, OPAMPs/TRIAMPs, ADC, LCD, and the variables for the digital filter and heart rate algorithms. After performing these initializations, the program enters the main loop.

4.2 ADC, OPAMPs, and TRIAMPs initialization

As explained in Schematic details of the Hardware Design chapter, the OPAMPs and TRIAMPs are used for amplifying and filtering the Doppler signal, while the ADC converts the signal to a digital value so that a digital filter as well as the frequency and heart rate calculation algorithms can be implemented.

The following table shows the type of operation in which each amplifier is configured for this application:

Table 4-1. Operation modes

Module	Operation mode
OPAMP0	General-purpose
OPAMP1	Non-inverting programmable gain amplifier
TRIAMP0	General-purpose
TRIAMP1	General-purpose

The ADC is configured to make conversions with a resolution of 8 bits, and the input signal is the one coming from OPAMP1.

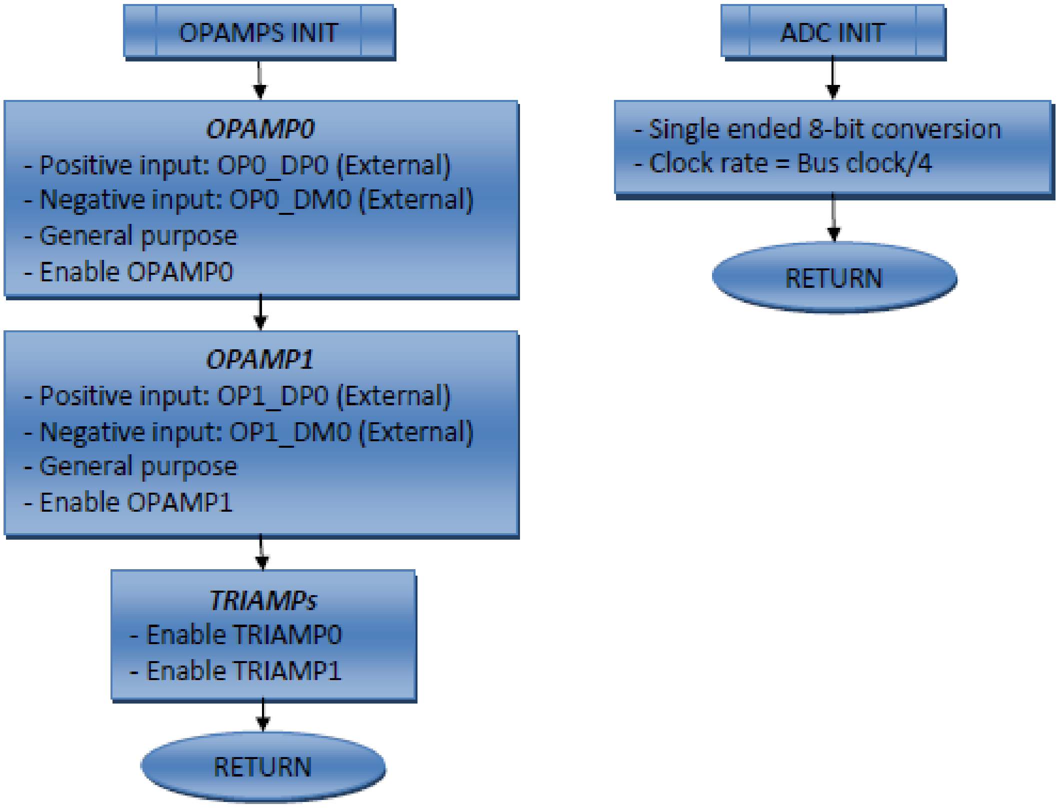


Figure 4-2. OPAMPs init and ADC init flow diagrams

4.3 Endless loop

During an infinite loop, the program executes the following four principal activities:

- Read and filter ADC data
- Plot graphs
- Calculate heart rate
- Update screen data

In order to plot graphs and data, the software includes the Freescale graphical LCD driver, configured to work with this application. For details on how to configure and use this driver, please visit http://www.freescale.com/egui.

The following flow diagram shows the outline of the endless repetitive loop.

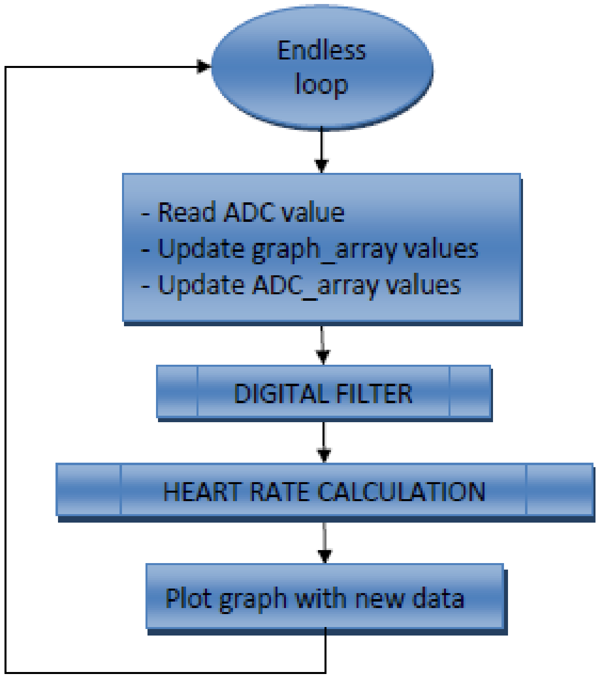


Figure 4-3. Main loop flow diagram

The loop starts by sampling and filtering the ADC data read from the Doppler instrumentation module. This filter helps to obtain the envelop of the sound signal.

When the data is ready to be processed, the beat detection algorithms recognize a heart pulse taking into account, the amplitude of the filtered signal, as well as the natural frequency.

4.3.1 Filter execution

The digital filter consists of a 100 order bandpass filter, whose fixed coefficients are listed in the variable uint8 BandPassCoef_4EKG[]. The lower frequency is set to 3 Hz and the upper frequency is 50 Hz.

```
uint8 BandPassCoef_4EKG[]= {0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 2, 2, 3, 4, 5, 6, 7, 9,10, 12,
15, 17, 20, 23, 27, 30, 34, 39, 43, 48, 53, 58, 63, 68, 73, 79, 84, 90, 95,100, 104, 109,
113, 116, 119, 122, 124, 125, 126, 127, 126, 125, 124, 122, 119, 116, 113, 109, 104, 100,95,
90, 84, 79, 73, 68, 63, 58, 53, 48, 43, 39, 34, 30, 27, 23, 20, 17, 15, 12, 10,9, 7, 6, 5,
4, 3, 2, 2, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0};
```

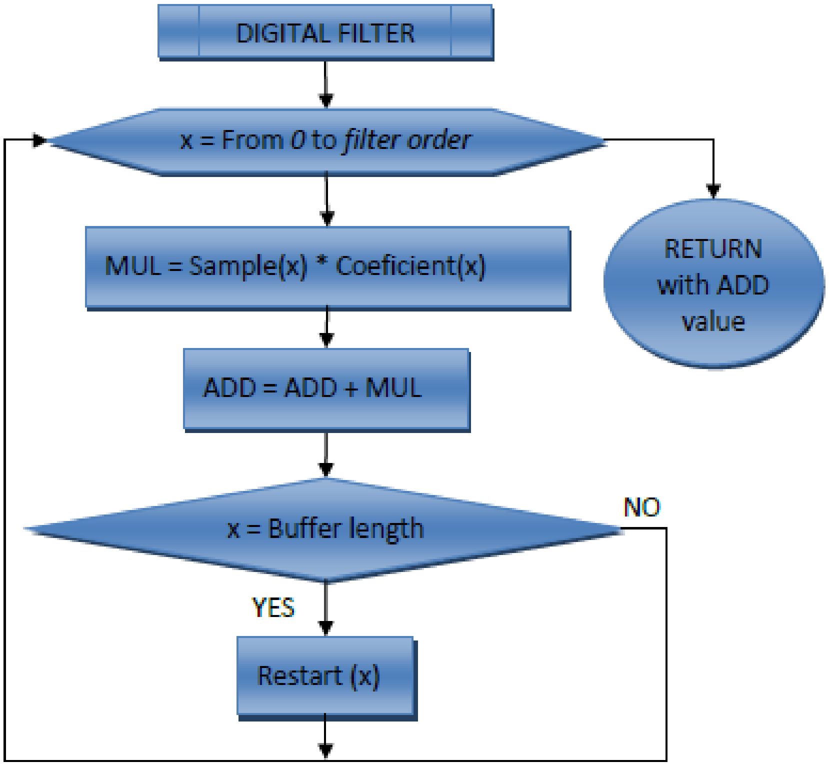


Figure 4-4. Filter execution flow diagram

The functioning of the digital filter as seen in Figure 4-4 consists of successive additions and multiplications with each of the samples taken with the ADC, which are stored in an array.

4.3.2 Heart rate calculation

The beats per minute (BPM) are calculated using an averaging method as described below:

1. First, a pulse detection algorithm is used to keep track of the exact time when the heart beats; this formula mixes threshold and frequency results.

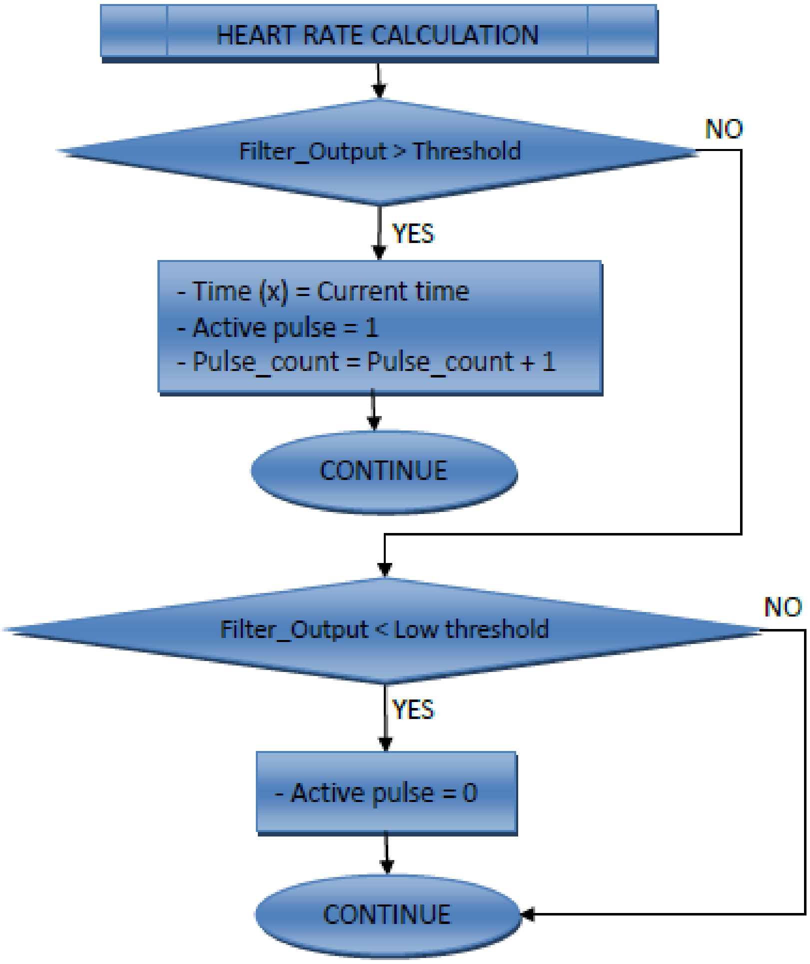


Figure 4-5. Heart rate calculation flow diagram

2. After the exact time of pulses has been saved, the program is ready to start the analysis for BPM calculation. The first formula obtains the instantaneous BPM, with the period between pulses in milliseconds.

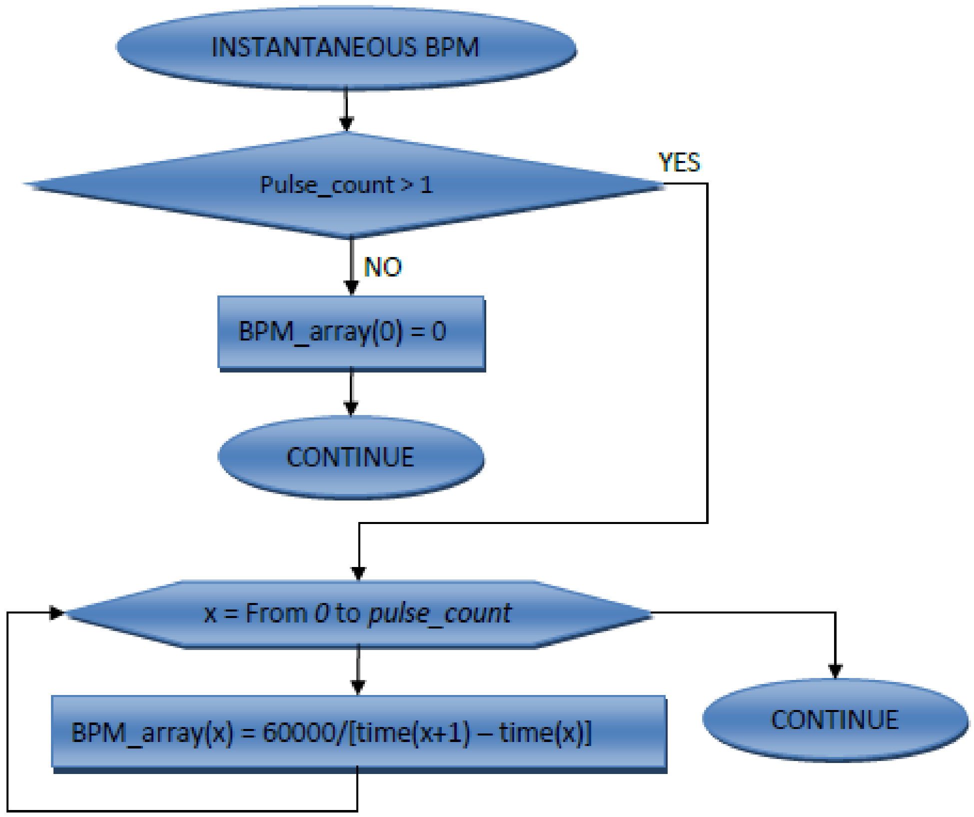


Figure 4-6. Instantaneous BPM calculation flow diagram

3. The next step is to order BPM array in ascending mode and obtain the average of a series of BPM data so that the measurement is more accurate. The highest and lowest values are eliminated to cancel any abnormal pulses. This action takes place only if five or more pulses have been detected.

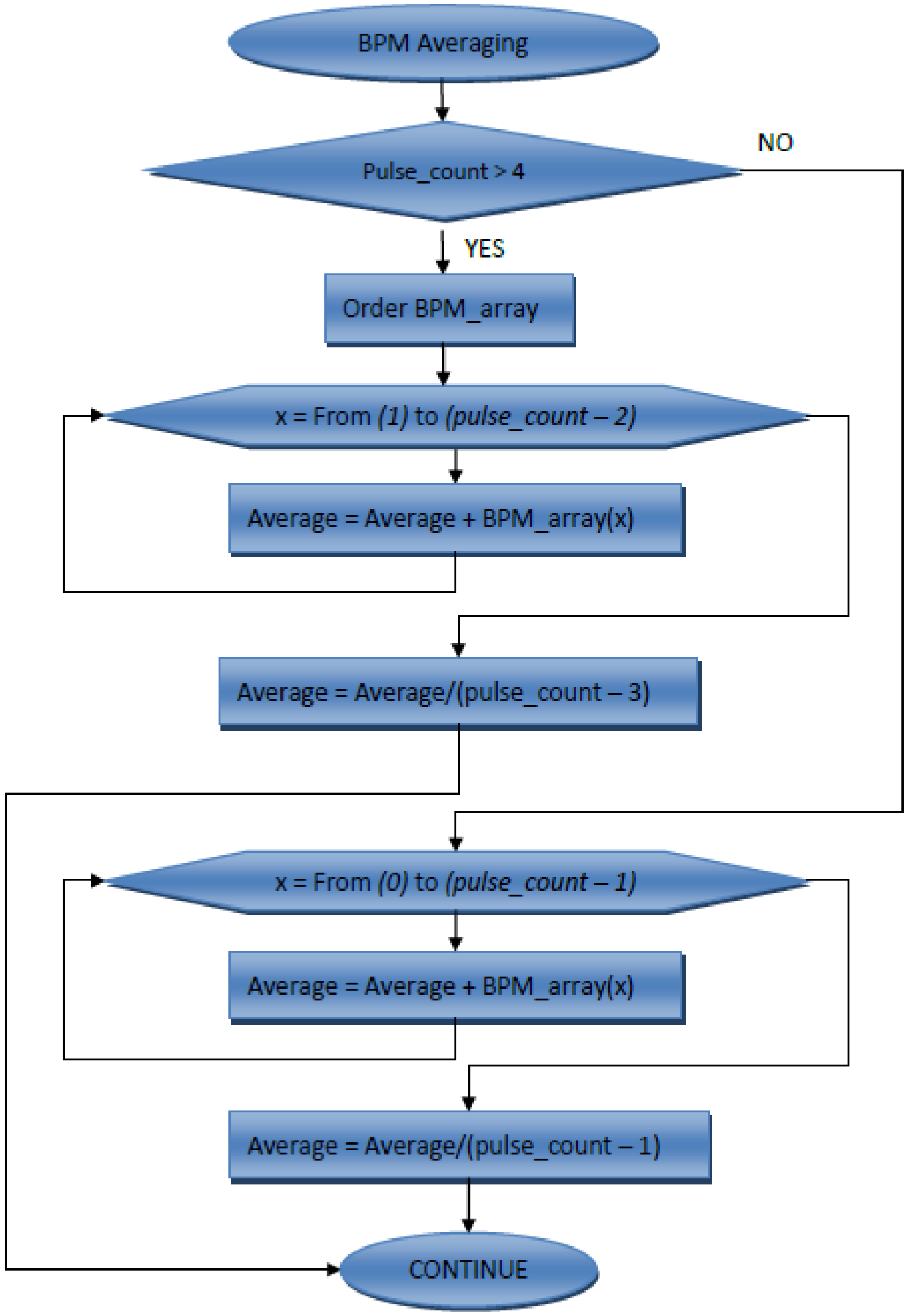


Figure 4-7. BPM averaging flow diagram

Chapter 5
Application Overview

5.1 Application description

This is a health monitoring reference application. It measures the heartbeats, calculates the beats per minute (BPM) and the sound frequency through the heart, and displays the information on the LCD.

5.1.1 Heartbeats detection

The output data of the digital filter provides an real-time signal that represents the heart rate waveform, from which the user can measure the amplitude of each pulse, compare it with an established amplitude value limit, and determine whether the pulse represents a heartbeat, or is a fake pulse.

5.1.2 Beats per minute

From the heart rate graph displayed and the heartbeats detected, the total number of heartbeats in a graph cycle and the time interval between each of them can be calculated. After this calculation, the average is obtained to get the correct heartbeats per minute.

5.1.3 Frequency

Frequency is a very important factor for heartbeats detection. Not only is the amplitude of the wave considered, but the 'tone' of the sound is also taken into account. This data is obtained from the slope of the samples; a higher difference between data means higher frequency.

5.2 Setup guide

This section includes the instructions to fully assemble the MED-STETH board and load the demo software. A quick explanation of how to use the application and interpret the information on the screen, is also provided.

5.2.1 Assembling the system

All of the following elements are required to correctly assemble the MED-STETH demo:

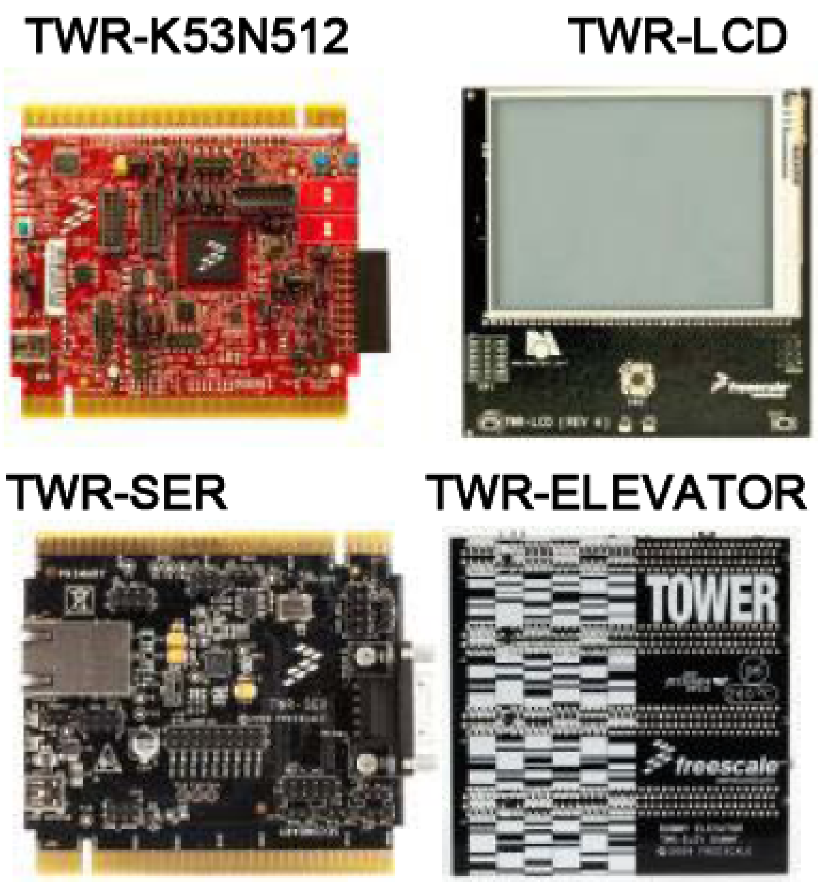


Figure 5-1. Tower system boards

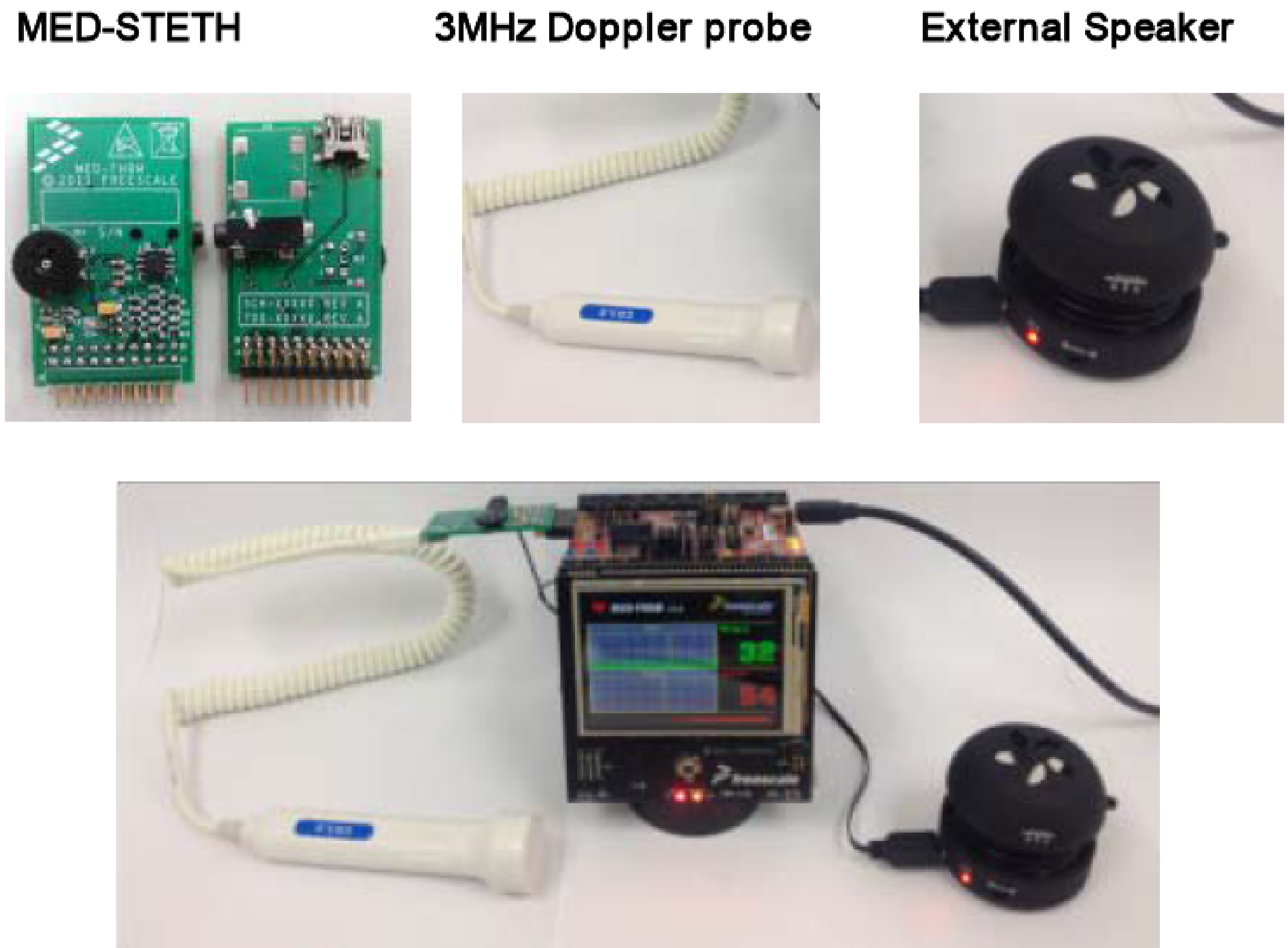


Figure 5-2. System's hardware working with K53N512 microcontroller

5.2.2 Loading the program for K53N512

After installing the CodeWarrior v10 software in your PC, complete the following steps to program the microcontroller:

1. Download the CW_FetalMonitor_RevX.zip from the Freescale webpage.
2. Open the CodeWarriorIDE and create the workspace folder.
3. After the CodeWarriorIDE window is shown, open the project:
   a. Choose File > Import.
   b. Select the "Select root directory" option and click Browse.
   c. Locate and select the downloaded CW_FetalMonitor_RevX unzipped folder.
   d. Make sure the "Copy projects into workspace" option is selected, and click Finish.

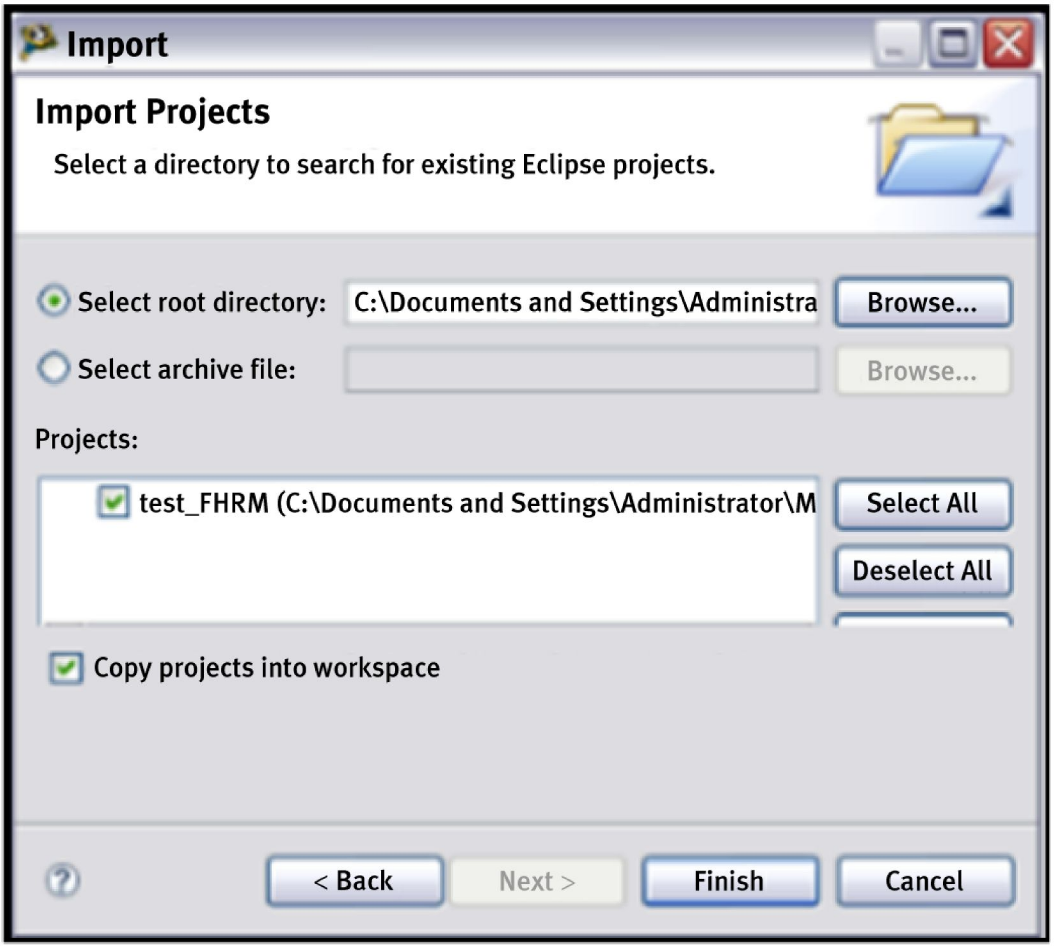


Figure 5-3. Project import window

4. In the CodeWarrior Projects section, look at the FetalMonitor project files, and select the project name.
5. From the Project menu, choose the Build Configurations/Set Active/ 2 MK53DN512Z_INTERNAL_FLASH option.
6. From the same Project menu, choose Build Project to compile the program.
7. After project building is completed, choose the Run option from the Run menu. In the window shown, select the INTERNAL_FLASH option again and click OK.

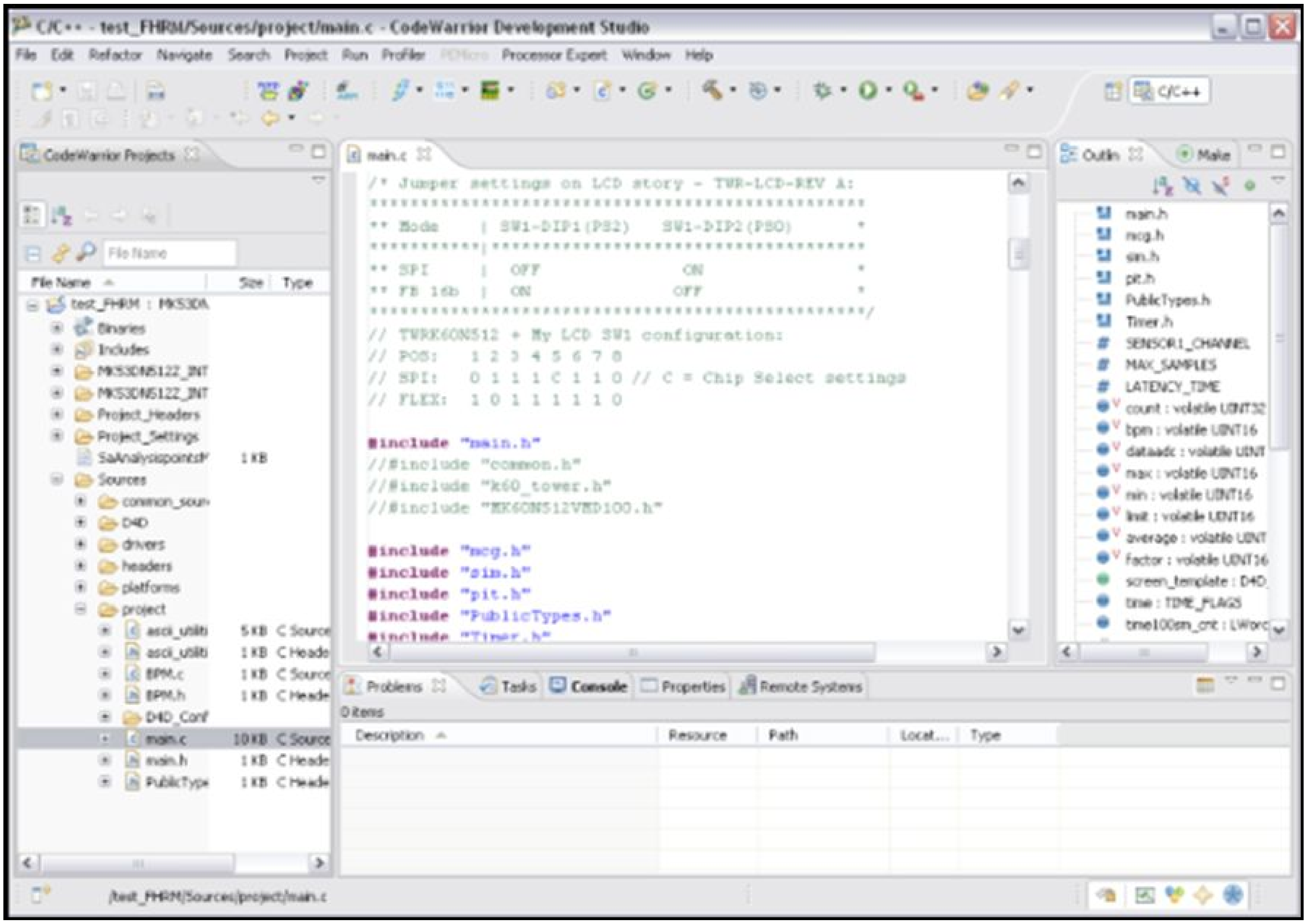


Figure 5-4. CodeWarrior main window

5.3 Using the MED-STETH

5.3.1 Functional demo

Once the tower system has been assembled and the firmware loaded in the microcontroller, make sure that the probe and the speaker are connected to the MED-STETH board.

1. Prepare the Doppler probe by smearing a little moisturizer on the top surface that will be in contact with the skin.
2. Place the face of the probe on the chest as shown in Figure 5-5.
3. Adjust the volume of the speakers in the probe's PCB and the position of the probe on the chest, so as to distinguish the sound of heartbeats.
4. If the above steps are followed correctly, the measurement graphics must be displayed on the TWR-LCD board.

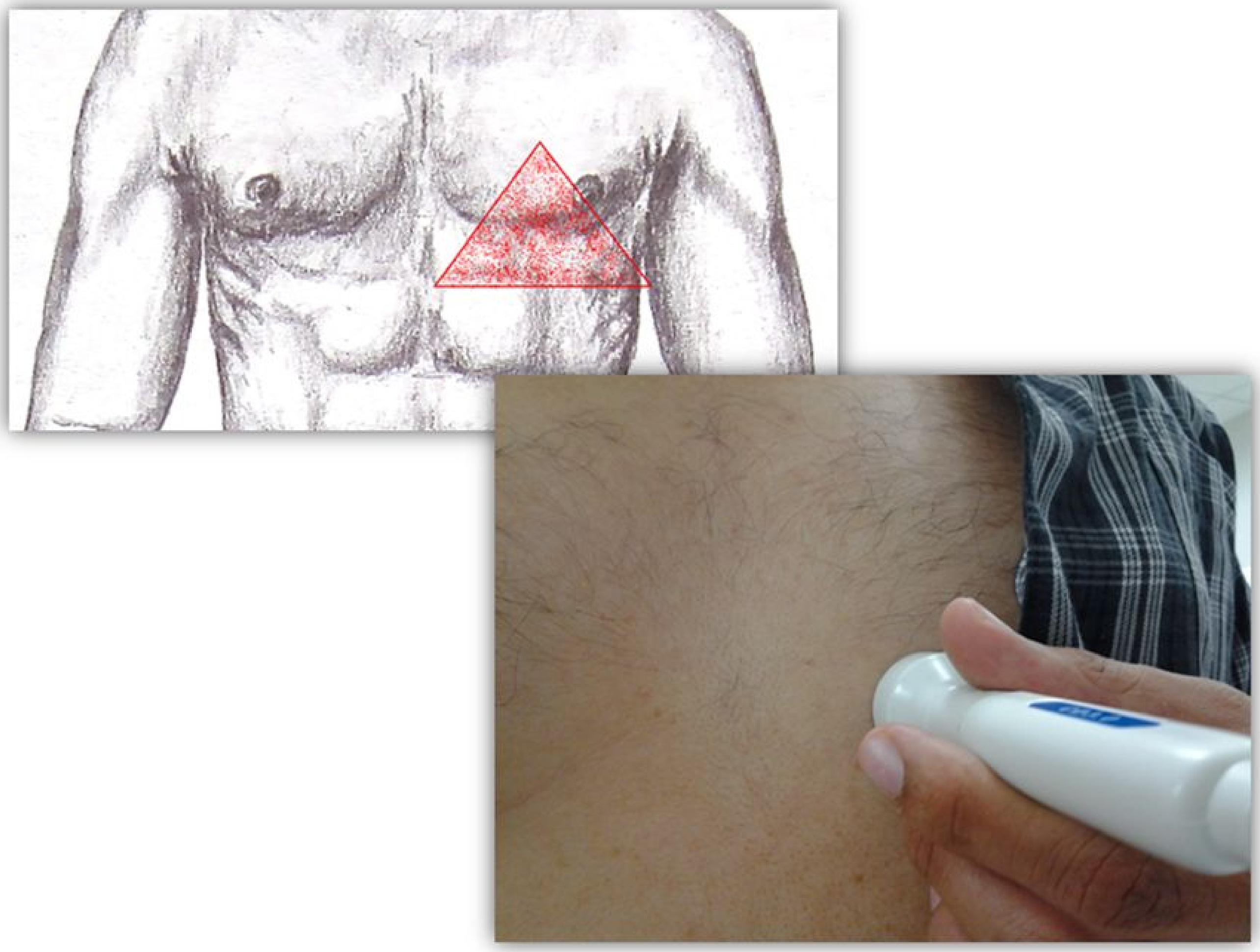


Figure 5-5. Probe placement

5.3.2 Graphical user interface features

- The name labels of the reference design MED-STETH v1.x and the Freescale logo appear at the top of the screen.
- The first graph shows the frequency of the heart sound.
- The number to the right of this graph is the average frequency of the sound.
- The second graph describes the heart waveform in time.
- The number to the right of this second graph represents the beats per minute of the corresponding heart rate waveform.

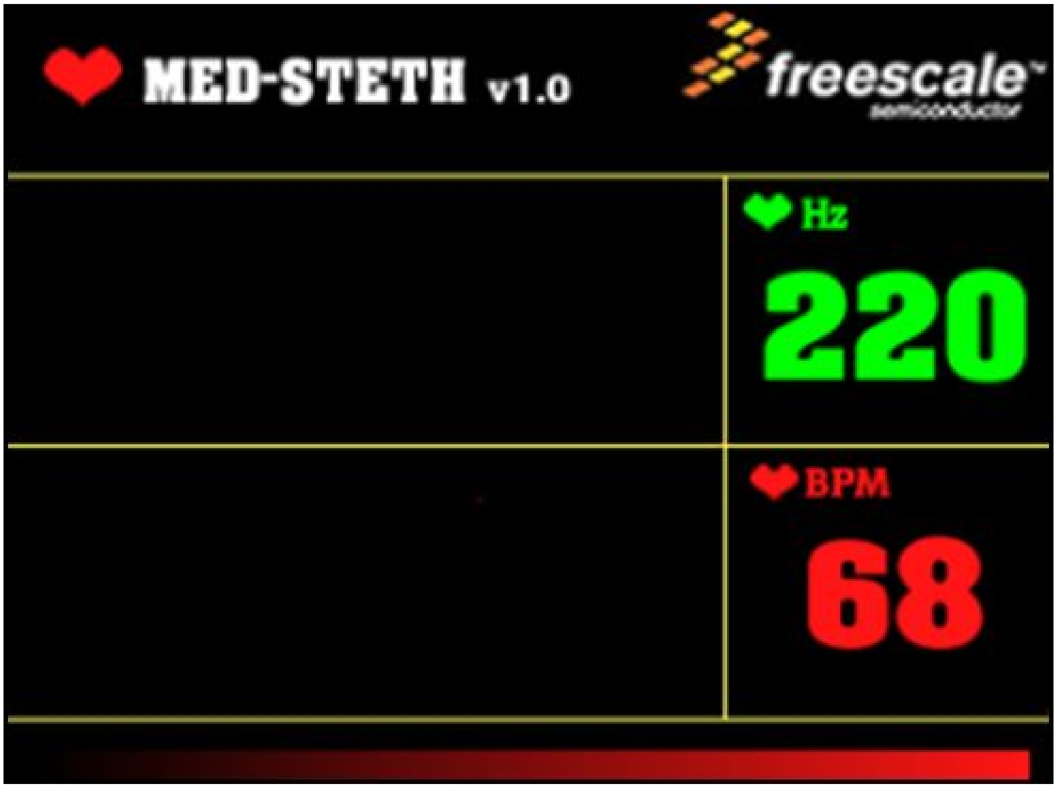


Figure 5-6. MED-STETH GUI

Chapter 6 References

6.1 Reference documents

- TWR-K53N512 Design Package (TWR-K53N512-PWB).
- Reference Manual and Data Sheet for Kinetis K53 (K53P144M100SF2RM, K53P144M100SF2).

Additional documentation may be found at http://www.freescale.com

6.2 Development tools

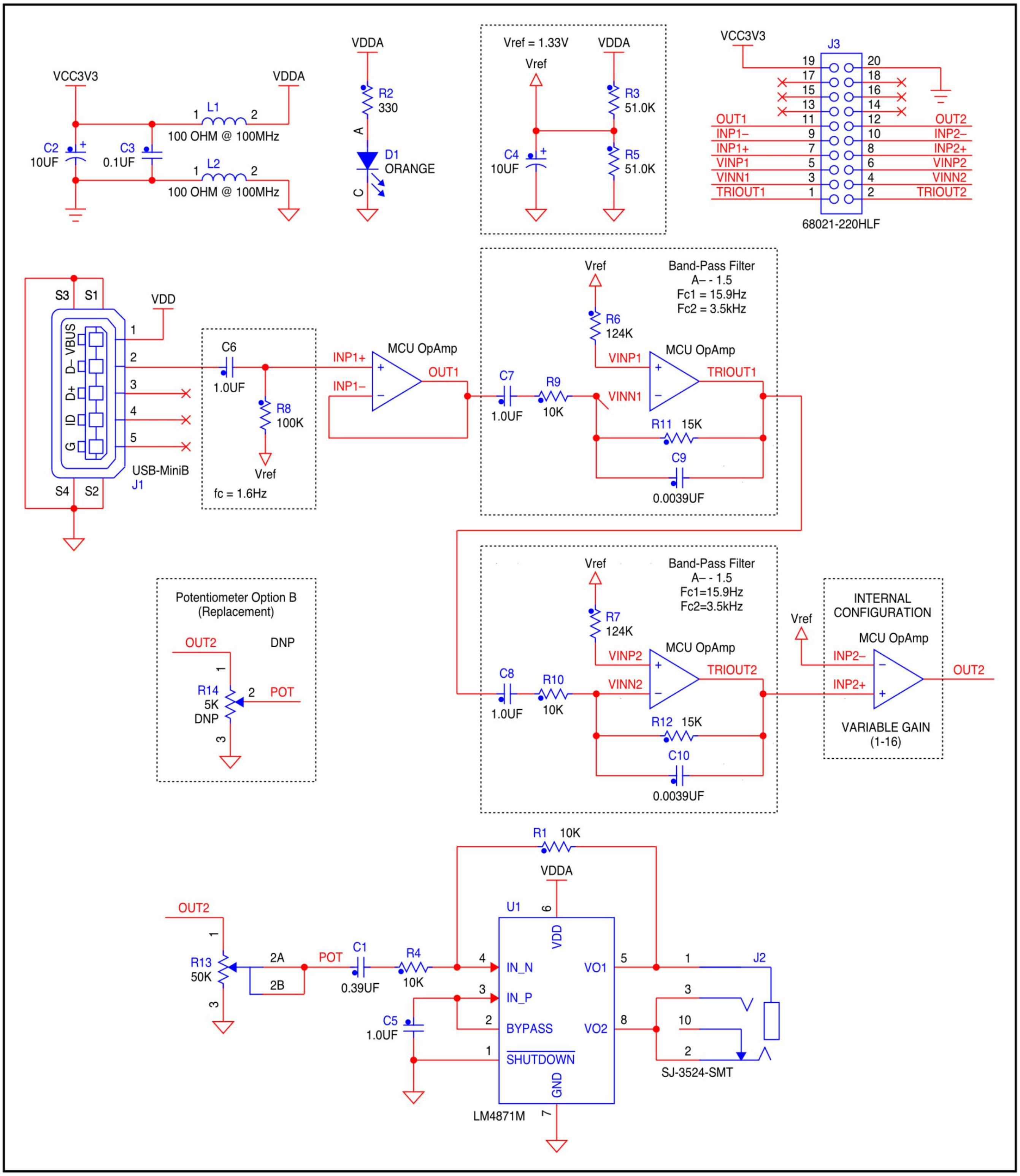
- CodeWarrior 10
- CodeWarrior 6.3
- Freescale Embedded GUI Converter Utility 2.1
- Allegro PCB Editor & Design Entry CIS

Chapter 7
Conclusions

7.1 Summary

Devices like MED-STETH provide a better accuracy and leads to more sophisticated and useful portable ultrasound devices which are really helpful in the diagnostics area. Freescale solutions help developers to introduce these devices faster in the market, providing tools that accelerate the design process and facilitate the implementation of reliable designs.

Appendix A
General schematic diagram



VCC3V3
VDDA
L1
100 OHM @ 100MHz
L2
100 OHM @ 100MHz
C2
10UF
C3
0.1UF
R2
330
D1
ORANGE
Vref = 1.33V
Vref
R3
51.0K
R5
51.0K
C4
10UF
J3
68021-220HLF
OUT1
INP1–
INP1+
VINP1
VINN1
TRIOUT1
OUT2
INP2–
INP2+
VINP2
VINN2
TRIOUT2
USB-MiniB
J1
VDD
C6
1.0UF
R8
100K
fc = 1.6Hz
MCU OpAmp
Band-Pass Filter
A– - 1.5
Fc1 = 15.9Hz
Fc2 = 3.5kHz
R6
124K
C7
1.0UF
R9
10K
R11 15K
C9
0.0039UF
Potentiometer Option B
(Replacement)
DNP
R14
5K
DNP
POT
R7
124K
C8
R10
R12 15K
C10
INTERNAL
CONFIGURATION
VARIABLE GAIN
(1-16)
R1 10K
U1
LM4871M
IN_N
IN_P
BYPASS
SHUTDOWN
VO1
VO2
GND
R13
50K
C1
0.39UF
R4
10K
C5
1.0UF
J2
SJ-3524-SMT

Appendix B
Microcontrollers description

Features	Kinetis 50 — K53DN512ZCMD10
Operating ratings	• Voltage range: 1.71 to 3.6 V • Max. digital supply current: 185 mA • Instantaneous maximum current single pin limit: –25 to 25 mA • Ambient temperature range: –40 to 85°C
Core	• 100 MHz ARM®Cortex™-M4 • DSP instructions delivering 1.25 Dhrystone MIPS per MHz.
Memory	• 512 KB flash • 128 KB RAM
Clock options	• 3 to 32 MHz crystal oscillator • 32 kHz crystal oscillator • Input clock frequency, 50 MHz external clock • Multipurpose clock generator
Communication	• Ethernet controller with MII and RMII interface to external PHY and hardware IEEE 1588 capability • USB full-/low-speed On-the-Go controller with on-chip transceiver • Three SPI modules • Two IIC modules • Six UART modules • Secure Digital host controller (SDHC) • IIS module
Analog	• Two 16-bit SAR ADCs • Programmable gain amplifier (PGA) (up to x64) integrated into each ADC. • Two 12-bit DACs • Two operational amplifiers (OPAMP) • Two transimpedance amplifiers (TRIAMP) • Three analog comparators (CMP) • Voltage reference

Table continues on the next page...

Features	Kinetis 50 — K53DN512ZCMD10
Timers	• Programmable delay block (PDB) • 8-channel timer: Motor control/general-purpose/PWM • Two 2-channel quadrature decoder/general purpose timers • IEEE 1588 timers • Periodic interrupt timers (PIT) • 16-bit low-power timer • Carrier modulator transmitter (CMT) • Real-time clock (RTC)

Appendix C
Bill of materials

Quantity	Part reference	Value	Description	MFG_NAME01	MFG_PN01	ASS Y_OPT
1	C1	0.39 µF	CAP CER 0.39 µF 16V 10% X7R 0603	KEMET	C0603C394K4RAC	YES
2	C2,C4	10 µF	CAP TANT 10 µF 6.3V 10% — 3216-18	AVX	TAJA106K006RNJ	YES
1	C3	0.1 µF	CAP CER 0.10 µF 25 V 10% X7R 0603	KEMET	C0603C104K3RAC	YES
4	C5-C8	1.0 µF	CAP CER 1.0 µF 6.3 V 10% X5R 0603	MURATA	GRM188R60J105KA01D	YES
2	C9, C10	0.0039 µF	CAP CER 0.0039 µF 25 V C0G 5% 0603	TDK	C1608C0G1E392J	YES
1	D1	ORANGE	LED OR SGL 30 mA 0805 SMT	KINGBRIGHT	APHCM2012SECK-F01	YES
1	J1	USB-MiniB	CON 5 USB2.0 MINI-B RA SHLD SKT SMT 0.8MM SP AU	HIROSE	UX60A-MB-5ST	YES
1	J2	SJ-3524-SMT	CON 4 AUD JACK 3.5 mm SMT — 211H AG	CUI INC	SJ-3524-SMT	YES
1	J3	68021-220HLF	HDR 2X10 RA TH 100 mil CTR 195H AU 120L	FCI	68021-220HLF	YES
2	L1, L2	100 Ω @100 MHz	IND FER BEAD 100 Ω@100 MHz 1A 25% 0603	TDK	MPZ1608D101B	YES
1	LS1	8 Ω	AUDIO DEVICE SPK TRANSDUCER 400–20000 Hz 8 Ω 0.7 W SMT	PUI AUDIO INC	SMS-1308MS-R	YES
1	R1	200 kΩ	RES MF 200 kΩ 1/10 W 5% 0603	VENKEL COMPANY	CR0603-10W-204JT	YES
1	R2	330 Ω	RES MF 330 Ω 1/10W 5% 0603	VENKEL COMPANY	CR0603-10W-331JT	YES
1	R3	75 kΩ	RES MF 75 kΩ 1/10 W 5% 0603	KOA SPEER	RK73B1JTTD753J	YES
3	R4, R9, R10	10 kΩ	RES MF 10 K 1/10W 5% 0603	KOA SPEER	RK73B1JTTD103J	YES

Table continues on the next page...

Quantity	Part reference	Value	Description	MFG_NAME01	MFG_PN01	ASS Y_OPT
1	R5	51.0 kΩ	RES MF 51.0 K 1/10W 1% 0603	KOA SPEER	RK73H1JTTD5102F	YES
2	R6, R7	124 kΩ	RES MF 124 kΩ 1/10 W 1% 0603	KOA SPEER	RK73H1JTTD1243F	YES
1	R8	100 kΩ	RES MF 100 kΩ 1/10 W 1% 0603	KOA SPEER	RK73H1JTTD1003F	YES
2	R11, R12	15 kΩ	RES MF 15 kΩ 1/10 W 5% 0603	VENKEL COMPANY	CR0603-10W-153JT	YES
1	R13	50 kΩ	RES VAR 50 K 0.03 W 20% — TH — Not recommended for new Design	PANASONIC	EVLHFKA01B54	YES
1	R14	5 kΩ	RES POT 5 kΩ 1/2 W 20% TH	BOURNS	3352T-1-502LF	DNP
1	U2	LM4871M	IC LIN AMP AUDIO PWR 3 W MONO 2-5.5 V SOIC8	NATIONAL SEMICONDUCTOR	LM4871M/NOPB	YES

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