

EKG-Based Heart-Rate Monitor Implementation on the LaunchPad Using MSP430G2xx

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MSP430 System Solutions

ABSTRACT

This application report describes a low-cost heart-rate monitor solution based on the MSP430™ LaunchPad Value Line Development Kit ([MSP-EXP430G2](#)), which uses the MSP430G2xx microcontroller (MCU). A daughterboard amplifies and filters the electrocardiogram (EKG) signal before it is sent to the MCU for sampling and processing. The heartbeat-per-minute data is sent to the PC by means of the back-channel UART-over-USB available on the LaunchPad. Additionally, an eZ430 radio frequency (RF) target can be connected to the six-pin header on the daughterboard to transmit data wirelessly via the SimpliciTI™ network protocol. The system can be powered by either universal serial bus (USB) power, a CR2032 3-V coin cell, or two AA or AAA batteries.

WARNING

The application presented here is for reference design purposes only and is not intended for any life-saving or medical-monitoring use.

Project collateral and source code discussed in this application report can be downloaded from the following URL:

http://software-dl.ti.com/msp430/msp430_public_sw/mcu/msp430/EKG-Based-Heart-Rate-Monitor/1_00_00_00/index_FDS.html.

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1 Introduction

The source of the human heart *beat* is an electrical pulse generated by a cluster of cells within the heart called the sinoatrial (SA) node [1]. This pulse travels from the SA node through the surrounding cells of the heart and then to the atrioventricular (AV) node. The AV node acts as a gate that allows the atria to finish contraction before allowing the pulse to move on to the ventricles. Each atrium pumps blood to a corresponding ventricle. The right atrium pumps blood to the right ventricle to provide blood to the lungs. The left ventricle, sourced by the left atrium, is the chamber that pumps blood throughout the body.

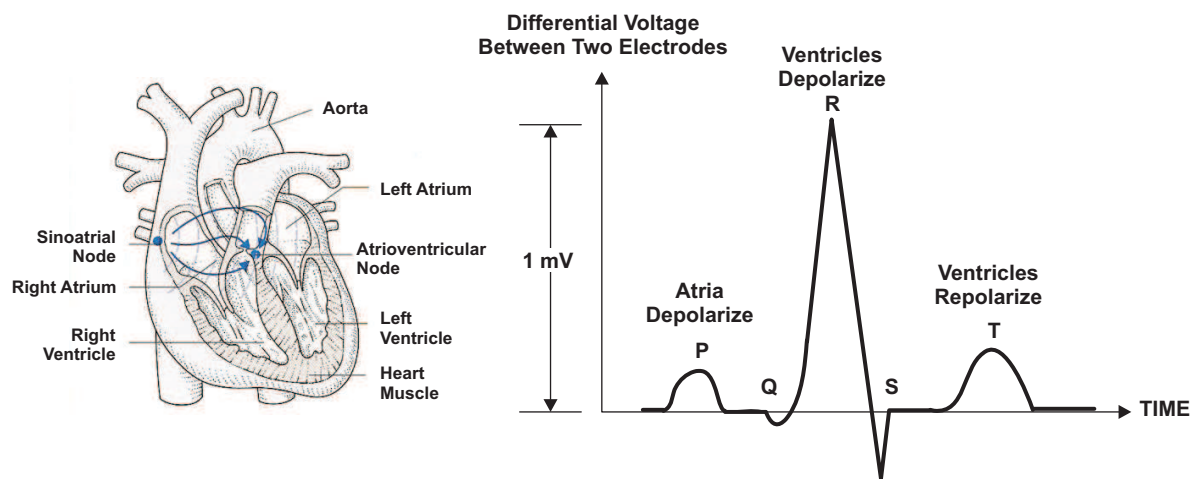


Figure 1. Human Heart Anatomy (left) and EKG Waveform (right)

The electrocardiogram (ECG) or elektrokardiogramm (EKG) is a medical standard for testing the human heart for defects and diseases [2]. Figure 1 shows the anatomy of the human heart and the waveform of the EKG signal. The EKG waveform can be used for extrapolation of data such as the number of heartbeats per minute (BPM) and the values can range from 30 to 200 BPM or 0.5 to 4 Hz.

The typical amplitude of the R wave component of the EKG signal is approximately 1 mV [3]. This peak is located within a group of peaks known as the QRS complex and represents the electrical pulse flowing through the ventricles. As this pulse travels via the blood stream, it can be detected at various points on the body. The extremities and the chest have become the standard locations for placing electrodes for acquiring the EKG signal. In this application, the subject's finger tips act as the differential point of contact with conductive pads to detect the EKG signal.

2 Hardware Description

The hardware is a daughterboard design attachable to the 10-pin headers on the LaunchPad development kit. The daughterboard contains the analog front-end components, battery connectors, headers, etc., whereas, the MSP430 MCU, the back-channel UART, and the eZ430 emulator circuit with the USB connector reside on the LaunchPad itself [4]. The schematic diagram of the hardware is shown in [Appendix D](#).

2.1 Hand Detection Circuit

A resistor divider scheme is implemented to detect contact of the subject's finger tips with the conductive pads. The premise of this scheme is that the resistance of the human body between the finger tips is in the 100 k Ω to 300 k Ω range, and the resistance placed between the conductive pads is significantly greater than this range, as shown in [Figure 2](#).

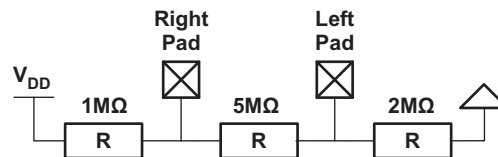


Figure 2. Hand Detection Circuit Diagram

When contact is made, the current flows through the path of least resistance (the human body) causing the voltage at the left conductive pad to change. This voltage is sampled by an analog-to-digital converter (ADC) channel and the digital conversion result is compared against a set of thresholds to determine good, bad, or no contact. Power and ground are supplied from the microcontroller pins and can be disconnected to minimize supply current consumption in sleep mode.

2.2 Analog Front End (AFE)

As mentioned previously, the amplitude of the EKG signal is approximately 1 mV peak-to-peak. The noise signals picked up by the human body (such as the 50 to 60-Hz line frequency) pose a serious problem to detecting the low-frequency low-magnitude EKG signal. An analog front end with a high gain with low cutoff filter frequency is necessary to condition this signal for digital conversion and processing. Because the common-mode signals from the conductive pads are the same, a differential amplifier simply cancels out the common-mode and amplifies the input differential EKG signal. The INA332 instrumentation amplifier is a low-cost differential amplifier used in this application and has a common mode rejection ratio (CMRR) specification of 73 dB up to 10 kHz, quiescent current of 490 μ A, and shutdown current levels less than 1 μ A. It can operate to a minimum supply voltage of 2.7 V with a dedicated shutdown pin. Additional instrumentation amplifier options relevant to this application are summarized in [3].

The INA332 is configured to a gain of 10 V/V with external 0.1% 10-k Ω resistors. The conductive pads are connected to the inputs with 51-k Ω resistors in series to limit the current from the human body and also act as a RC low-pass filter. The 5-M Ω pull-down resistors from the pads to common mode voltage (VCM) help keep the voltage identical on both inputs and also provide a dc bias point for circuit operation. The VCM voltage is generated by a general-purpose op-amp in the voltage-follower (low-output impedance) configuration to 750 mV.

The TLV274 is a quad operational amplifier (op-amp) used in this application with supply currents of 550 μ A/channel and minimum supply voltage of 2.7 V. With a CMRR of 58 dB, the op-amps are used to implement a second-order Sallen-Key low pass filter (LPF) with gain of each stage at 8.5 V/V. The overall gain of the AFE is $10 \times 8.5 \times 8.5 = 722.5$ V/V, and the cutoff frequency is 16 Hz. Additional general-purpose op-amp options relevant to this application are also summarized in *Heart-Rate and EKG Monitor Using the MSP430FG439* ([SLAA280](#)) [3].

The resulting amplified and conditioned EKG signal output from the LPF is fed to the ADC channel of the MSP430 microcontroller for conversion and processing. The shutdown pin of the INA332 and the V_{CC} pin of the TLV274 are connected to one general-purpose input/output (GPIO) pin of the MSP430 to enable or disable the AFE. The GPIO pin is set to a low state to minimize supply current consumption in sleep mode. As a precautionary measure, the AFE has protection diodes (TPD2E001) on the conductive pads to prevent human electrostatic discharge (ESD) from causing component failure.

2.3 LaunchPad Port/Pin to Functionality Mapping

The LaunchPad Development Kit has a 20-pin PDIP socket that a 14-pin or a 20-pin MCU can be plugged into. The MSP430G2452 was used for this application and has 8 KB of Flash, 256 B of RAM, 1 Timer_A3 and 8-channel ADC10 [11]. The LaunchPad port/pin mapping is designed to match the pinout of the MSP430G2xx family of devices.

The port/pin functionality mapping for the left and right header pins on the LaunchPad are shown in Table 1 and Table 2, respectively.

Table 1. LaunchPad Port/Pin Functionality Mapping – Left Header

Port/Pin Name	Signal Name	Description
V _{CC}	V _{DD}	Power (V _{DD}) for the MSP430
P1.0 (LED1)	LED_RED	Indicates bad contact
P1.1 (TXD)	UART_TXD	UART transmit (TX) line
P1.2 (RXD)	UART_RXD	UART receive (RX) line
P1.3 (S2)	P1_3 (SW2)	Push button switch
P1.4	EKG	Input to the ADC to sample filtered and amplified EKG signal
P1.5	HAND_LEFT	Input to the ADC to sample hand-detection circuit signal
P2.0	N/A ⁽¹⁾	N/A ⁽¹⁾
P2.1	N/A ⁽¹⁾	N/A ⁽¹⁾
P2.2	N/A ⁽¹⁾	N/A ⁽¹⁾

⁽¹⁾ Not used in this application.

Table 2. LaunchPad Port/Pin Functionality Mapping – Right Header

Port/Pin Name	Signal Name	Description
GND	GND	Ground (GND) for the MSP430
XIN	P2_6	V _{DD} for hand detection circuit
XOUT	SHUTDOWN	Enable/disable the AFE
TEST	TEST	Spy-Bi-Wire programming pin for the MSP430
(S1) RST	RESET (SW1)	Reset switch for the MSP430 (Spy-Bi-Wire programming pin)
P1.7	P1_7	GND for hand detection circuit
(LED2) P1.6	LED_GREEN	Indicates good contact
P2.5	N/A ⁽¹⁾	N/A ⁽¹⁾
P2.4	N/A ⁽¹⁾	N/A ⁽¹⁾
P2.3	N/A ⁽¹⁾	N/A ⁽¹⁾

⁽¹⁾ Not used in this application.

2.4 eZ430 RF Target Header

The hardware has a six-pin header that has power/ground connections and UART lines coming from the LaunchPad. This header allows for an eZ430 RF target such as the eZ430-RF2500 to be connected for wireless data transmission [5]. Appendix C has details on target boards with different frequencies and the SimpliciTI wireless UART demo software for programming them that are provided with this application report.

2.5 Power Supply Setup

With the daughterboard attached to the LaunchPad, there are multiple ways of powering up the system.

NOTE: The system is designed to be powered from only one power source at a time. The system should be powered from either USB or coin-cell or 2x AA or 2x AAA batteries.

USB Power:

1. Populate all of the jumpers on the LaunchPad (V_{CC} , RXD, TXD, TEST, RST).
2. Remove the jumper JP1 on the daughterboard.
3. Connect the micro-USB cable from the LaunchPad to the PC. The 5 V from USB supply goes through a 3.3 V LDO and powers the whole system. The USB cable also serves as a MSP430 application UART connection to the PC [4].

WARNING

When powering the system from USB, disconnect all batteries (coin-cell or 2x AA/AAA) connected to the system. If any battery remains plugged in, there is a risk of the battery being charged that could lead to an explosion, which causes potential for property damage, personal injury or death.

External Battery Power:

1. Remove all LaunchPad jumpers (V_{CC} , RXD, TXD, TEST, RST).
2. Populate the jumper JP1 on the daughterboard.
3. Plug in the battery to connector B1 to power the system from one 3 V CR2032 coin-cell battery or plug in the connector to header B2 to power the system from two AA/AAA batteries.

WARNING

When powering the system from batteries, either the coin-cell or the 2x AA/AAA batteries connector should be plugged in. If both are connected together, there is a risk of one battery charging other that could lead to an explosion, which causes potential for property damage, personal injury or death.

[Table 3](#) shows the supply current consumption of the system in different power modes.

Table 3. Supply Current Consumption

System State	Supply Current (Typical)
Active mode (without eZ430 RF target)	2.1 mA
Active mode (with eZ430 RF target attached)	2.5 mA
Sleep mode (with eZ430 RF target attached) ⁽¹⁾	2 μ A

⁽¹⁾ System is in low-power mode 3 (LPM3).

3 Software

The flow chart for this application software is shown in [Figure 3](#).

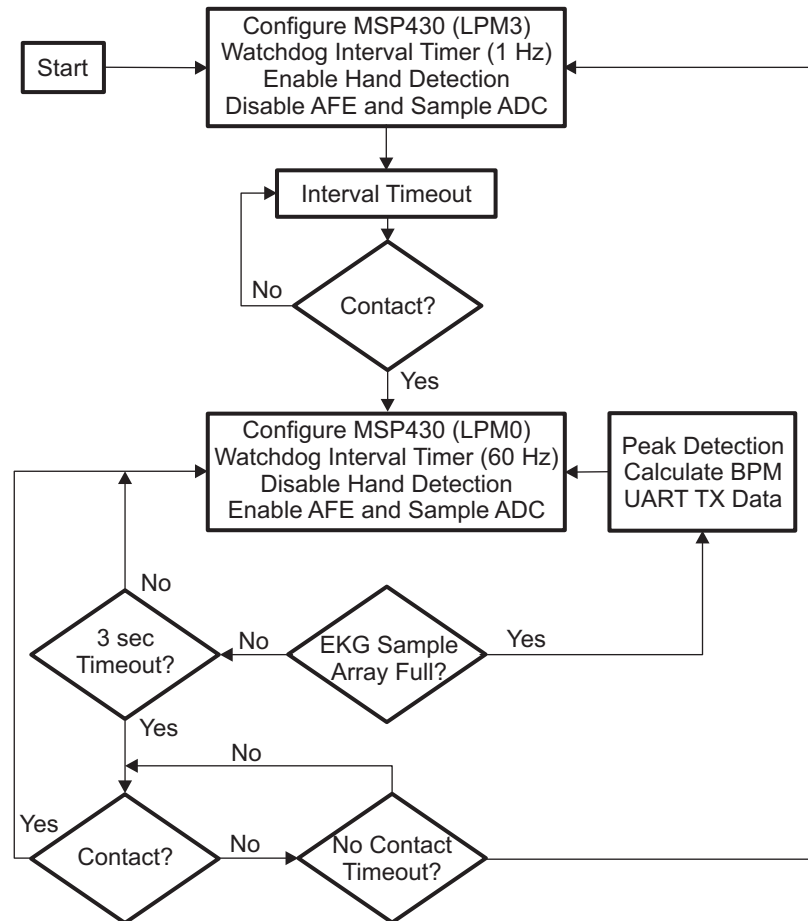


Figure 3. Software Flowchart

It begins by initializing the MSP430 in LPM3 sleep mode, configuring the watchdog timer in interval-timer mode (sourced by ACLK/VLO), and disabling the AFE. When the interval (approximately 1 second) expires, the ADC is triggered for single-channel single conversion. With the hand-detection circuit enabled, the left pad is sampled by the ADC and compared against a set of thresholds to determine the quality of contact. If the voltage on the left pad exceeds 1.7 V, the contact is considered good, and the green LED on the LaunchPad flashes briefly. If the voltage exceeds 1.5 V, the contact is considered bad and the red LED flashes briefly. The default value on the pad for no contact is 0.825 V (with 3.3-V supply voltage).

If there is no contact, the MSP430 goes back into LPM3 sleep mode until the interval expires again. If there is contact (good or bad), the hand-detection circuit is disabled, the AFE is enabled, the watchdog interval timer is sourced from MCLK/DCO, and the sleep mode changed to LPM0. The DCO runs with a calibrated value of 1 MHz, and the interval timer runs at 60 Hz. Therefore, the ADC is triggered to sample the amplified and filtered EKG signal at output of the AFE every 16 milliseconds. The digital conversion values are stored in memory and are used by the heart rate detection algorithm to compute the number of heartbeats per minute [9].

The heart rate value is transmitted via a Timer-A based UART [10]. The UART output can be relayed to the PC by means of either the back-channel UART-over-USB connection on the LaunchPad or the eZ430 RF target header on the daughterboard. During the EKG sampling by the ADC, the hand-detection circuit is momentarily enabled every three seconds to ensure that contact is being made. If there is contact, the application goes back to EKG sampling. If not, the hand-detection circuit remains enabled, and the applications keeping checking for contact for approximately 10 seconds. If there is still no contact, the AFE is disabled and the MSP430 returns back to the initial LPM3 state where it checks for contact every second.

Details on programming the software on the heart-rate monitor setup are provided in [Appendix B](#) and the eZ430 RF target boards in [Appendix C](#). [Figure 4](#) shows the complete hardware setup in action (left side) and the UART output log display on the HyperTerminal application window on the PC (right side).

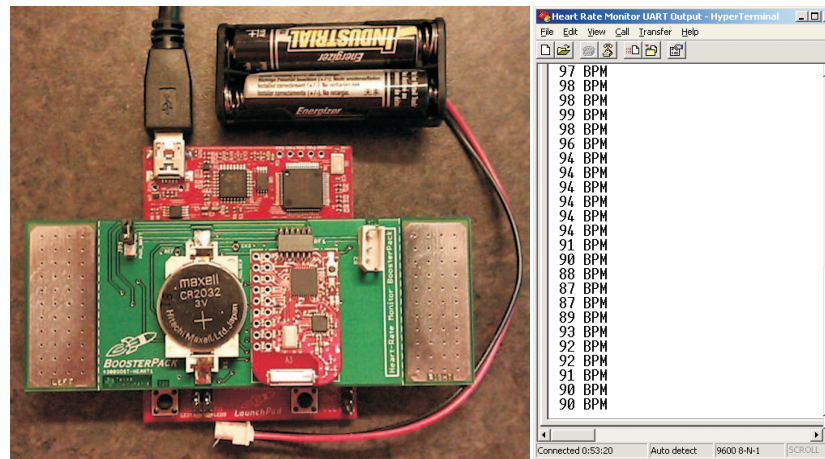


Figure 4. Heart-Rate Monitor Setup (left) and UART Output on PC (right)

4 References

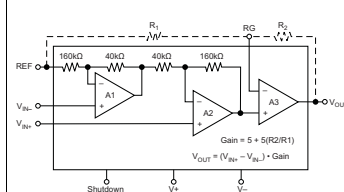
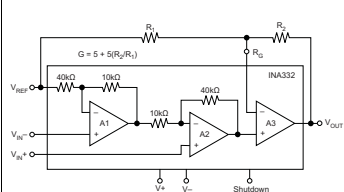
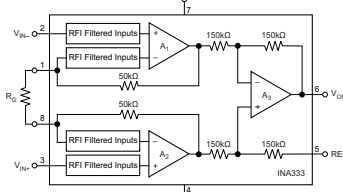
1. http://www.daviddarling.info/images/sinoatrial_node.jpg
2. <http://www.medterms.com>
3. *Heart-Rate and EKG Monitor Using the MSP430FG439 (SLAA280)*
4. *MSP-EXP430G2 LaunchPad Experimenter Board User's Guide (SLAU318)*
5. *eZ430-RF2500 Development Tool User's Guide (SLAU227)*
6. A2500R24A-EZ4x - Integrated Radio (AIR) EZ4x Module Series Product Brief: Anaren (<http://www.anaren.com>)
7. AMB8423-EM – 868 MHz Radio Module for TI Development Tool eZ430-RF2500 Datasheet: Amber Wireless (<http://www.amber-wireless.de/index.php>)
8. *Wireless Sensor Monitor Using the eZ430-RF2500 (SLAA378)*
9. Sourabh Ravindran, Steven Dunbar, and Bhargavi Nisarga, *Real-Time, Low-Complexity, Low Memory Solution to ECG-Based Heart Rate Detection*, IEEE Engineering in Medicine and Biology Society (EMBC), 2009. (<http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05334447>)
10. *Implementing a UART Function With TimerA3 (SLAA078)*
11. *MSP430G2x52, MSP430Gx12 Mixed Signal Microcontroller Datasheet (SLAS722)*

Appendix A Amplifier Options

A.1 Instrumentation Amplifier Options

This reference design uses the INA332 as the instrumentation amplifier for the analog front end. Table 4 shows other options for the instrumentation amplifier.

Table 4. Instrumentation Amplifier Comparison

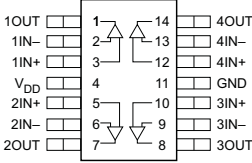
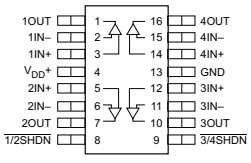
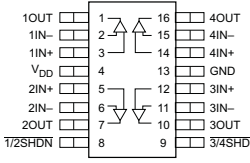
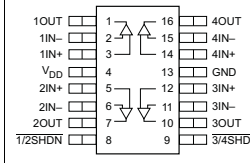
Device Name	INA321	INA332	INA333
	 <p>Gain = $5 + 5(R2/R1)$ $V_{OUT} = (V_{IN+} - V_{IN-}) \cdot \text{Gain}$</p>	 <p>Gain = $5 + 5(RG/R1)$</p>	 <p>Gain = $1 + \left(\frac{100k\Omega}{R_G}\right)$</p>
Quiescent current	40 $\mu\text{A}/\text{channel}$	490 $\mu\text{A}/\text{channel}$	50 $\mu\text{A}/\text{channel}$
Shutdown current	< 1 μA	~ 0.01 μA	No shutdown
Bandwidth	500 kHz, G = 5 V/V	2 MHz, G = 25	35 kHz, G = 10
Slew rate	500 kHz, G = 5 V/V	5 V/ μs for G = 25	0.16 V/ μs for G = 1
Supply voltage	2.7 V – 5.5 V	2.7 V – 5.5 V	1.8 V – 5.5 V
Price/1ku (listed on http://www.ti.com)	1.25	0.55	1.80

The INA321 is pin-to-pin compatible with the INA332 and uses a two-resistor feedback network to set the gain. It also offers significantly lower quiescent current, although it costs more. The INA333 has a different architecture in which the gain is set by one resistor. While it lacks a shutdown pin, the quiescent current consumption levels are comparable to the INA321 with the advantage of operating as low as 1.8 V. While the most expensive of the three, the INA333 is ideal for battery-operated portable systems with low-voltage operating range.

A.2 Operational Amplifier Options

This reference design uses the TLV274 as the op-amp for the Sallen-Key low pass filter implementation. [Table 5](#) shows other options for the operational amplifier.

Table 5. Operational Amplifier Comparison

Device Name	TLV274	TLV2375	TLV2765	TLV2785
				
Supply current	470 μ A/channel ($V_{DD} = 2.7$ V)	470 μ A/channel ($V_{DD} = 2.7$ V)	20 μ A/channel	650 μ A/channel
Shutdown current	No Shutdown	~ 25 μ A	~10 nA	900 nA
UGBW	2.4 MHz ($V_{DD} = 2.7$ V)	2.4 MHz ($V_{DD} = 2.7$ V)	500 kHz	8 MHz
Slew rate	2.1V/ μ s ($V_{DD} = 2.7$ V)	2 V/ μ s ($V_{DD} = 2.7$ V)	0.2 V/ μ s ($V_{DD} = 2.4$ V)	4.8 V/ μ s ($V_{DD} = 2.7$ V)
Supply voltage	2.7 V – 16 V	2.7 V – 16 V	1.8 V – 3.6 V	1.8 V – 3.6 V
Price/1ku (listed on http://www.ti.com)	0.46	0.85	1.50	1.60

The TLV2375 has specifications similar to the TLV274 with the additional capability of shutdown pins. The TLV2765 and TLV2785 can operate in low-voltage range with sub-microamperes of current consumption in shutdown mode.

Appendix B Wired USB Demo With Back-Channel UART

The default setup for the heart-rate monitor uses the onboard emulator circuit on the LaunchPad to send data from the MSP430G2xx MCU UART through the USB to the PC. Virtual COM port drivers should be installed on the PC so that the USB connection appears as the MSP430 application UART. These drivers should be on the system by default when either IAR Embedded Workbench or Code Composer Studio IDE are installed. If a system is devoid of any MSP430 development tools, the drivers can be installed by referring to the executable file in reference link [8].

To setup the system with USB:

1. Populate all of the jumpers on the LaunchPad (V_{CC} , RXD, TXD, TEST, RST).
2. Remove the jumper JP1 on the daughterboard.
3. Attach the daughterboard to the LaunchPad.
4. Connect the mini-USB cable from the LaunchPad to the PC.

The zip file associated with this application report has two folders that contain source code and project files for IAR Embedded Workbench™ v5.10 and Code Composer Studio™ v4.2.1 IDE.

To download the source code in IAR Embedded Workbench, see the folder: *Software/Heart Rate Monitor/IAR*.

1. Open the Project: File → Open Workspace and select *HRM.eww*. If needed, select Project → Add Existing Project and select *HRM.ewp*.
2. Compile the project: Project → Make.
3. Download the code: Project → Download and Debug.
4. Run the code: Debug → Go.

To download the source code in Code Composer Studio, see the folder: *Software/Heart Rate Monitor/CCS*.

1. Import the Project: Project → Import Existing CCS/CCE Eclipse Project and select the Code Composer Studio folder as the search directory. Select *HRM* to import the project and source code.
2. Compile the project: Project → Rebuild All.
3. Download the code: Target → Debug Active Project.
4. Run the code: Target → Run.

The UART output from the MCU can be viewed on the PC via HyperTerminal.

1. Go to Start Menu → Accessories → Communications → HyperTerminal.
2. Enter a name for the connection and select the virtual COM port for the MSP430 Application UART applicable to the LaunchPad Development Kit. To find the appropriate COM port number, open up Device Manager → Ports (COM & LPT) and select the COM port titled MSP430 Application UART.
3. Change the bits per second to 9600 baud and click OK. If necessary, select Call → Call.

Appendix C Wireless UART Demo With the eZ430 RF Target Board

The heart-rate monitor hardware has a six-pin eZ430 connector to which an RF target board can be connected, allowing heart-rate data to be transmitted wirelessly to another RF target board connected to a PC (access point). This configuration serves as an alternative to the back-channel UART-over-USB cable and can be used with a 3-V CR2032 coin cell battery or two AA or AAA batteries.

An example of the RF target board is the eZ430-RF2500 Development Tool Kit from Texas Instruments, which comes with an eZ430 emulator for programming and debugging the RF target board. The RF target contains the MSP430F2274 microcontroller linked to the transceiver chip, CC2500, for 2.4-GHz operation. The MSP430F2274 is programmed via the Spy-Bi-Wire (2-wire JTAG) protocol. For more details on the hardware specifications, see the *eZ430-RF2500 Development Tool User's Guide* (SLAU227) [5].

RF target boards with the same form factor and pinout, but different frequency ranges, are available from vendors such as Anaren [6] and Amber Wireless [7]. Table 6 shows the options.

Table 6. eZ430 RF Target Boards

Manufacturer	Part Number	Transceiver Chip	Frequency
Texas Instruments	eZ430-RF2500	CC2500	2.4 GHz
Anaren	A2500R24A-EZ4	CC2500	2.4 GHz
Anaren	A1101R09A-EZ4	CC1101	900 MHz
Amber Wireless	AMB8423	CC1101	868 MHz

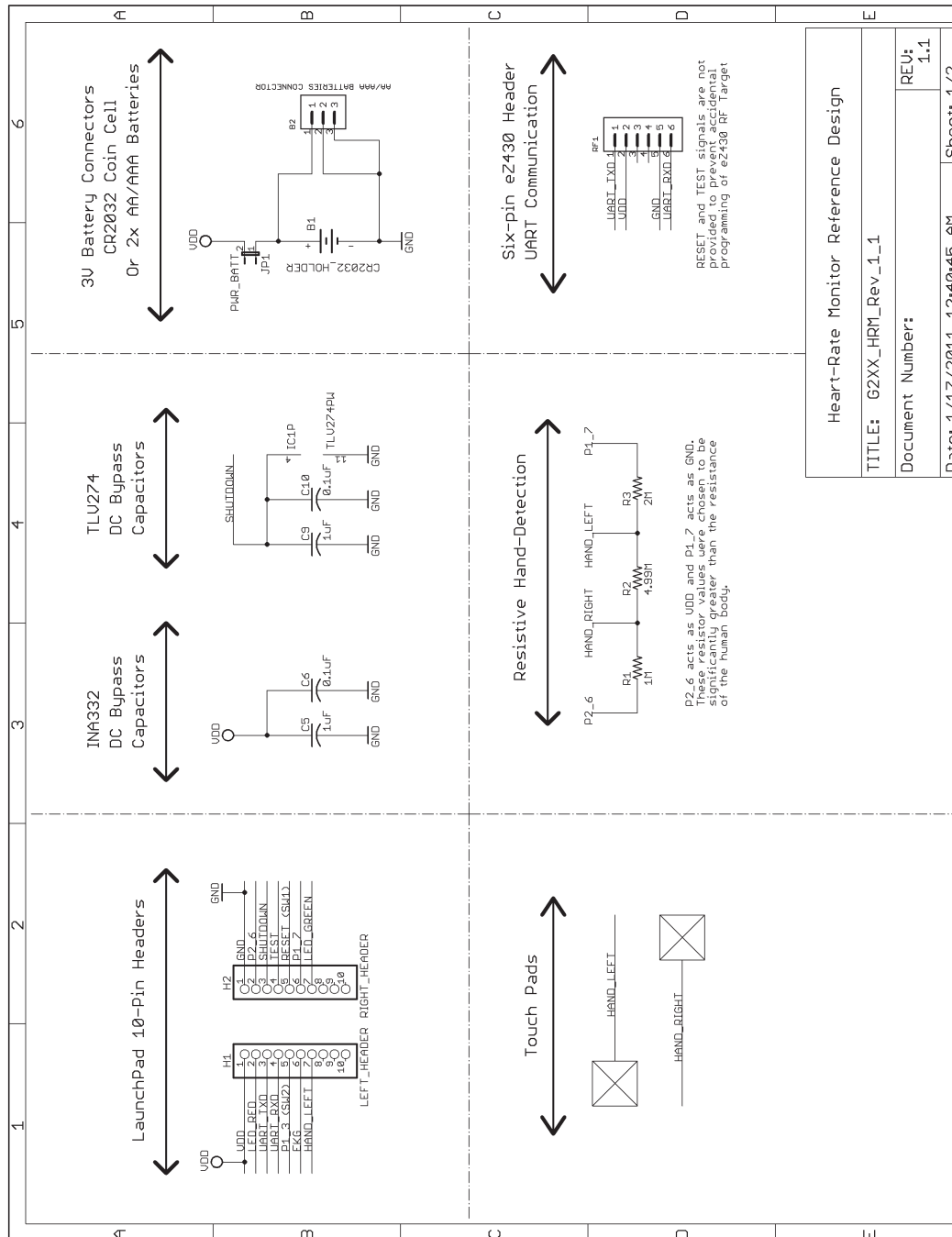
The software for programming the RF target boards and demonstrating wireless capability is provided in the zip file available for download along with this application report. The source code is written in C and project files are provided for both IAR Embedded Workbench 5.10 and Code Composer Studio v4.2.1 IDEs. The software is based on the wireless sensor demo using the eZ430-RF2500 and uses the two RF target boards supplied with the tool kit [8].

NOTE: If using the IAR Embedded Workbench Full Version, the existing project settings will not work properly. Go to Project Options → Linker → Extra Options and uncheck the *Use command line options -- ks_version*. This extra option is required to overcome the 4 KB code size limitation of the Kickstart version only.

One RF target board serves as the end point and the other serves as the access point. The end-point target board (connected to the hardware via the six-pin connector, as previously mentioned) receives data via UART (9600 baud) and transmits it via the SimpliciTI protocol to the access point. When not receiving bytes from the UART, the RF target turns off the antenna/transceiver and goes into LPM3 to prevent battery drain. The access point target board (connected to the eZ430 emulator plugged into the USB port of a PC) receives data via the SimpliciTI protocol from the end point. It then outputs that data via backchannel UART-over-USB, and the data can be displayed on a HyperTerminal on the PC at the rate of 9600 baud (see Appendix B).

To compile the source code files for the RF target boards with either CC2500 or CC1101, two project files have been provided with pre-existing settings and are named to reflect the transceiver being used. Details on compiling the project, function call descriptions, and setting up the UART and HyperTerminal can be found in the reference documents [4] and [7]. The zip files associated with these application reports contain the COM port drivers essential for the eZ430 emulator to function as the MSP430 application UART.

Appendix D Hardware Schematic Diagrams



Heart-Rate Monitor Reference Design	
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Date:	1/17/2011 12:40:45 AM
	Sheet: 1/2

Figure 5. Hardware Schematic Diagram (Page 1/2)

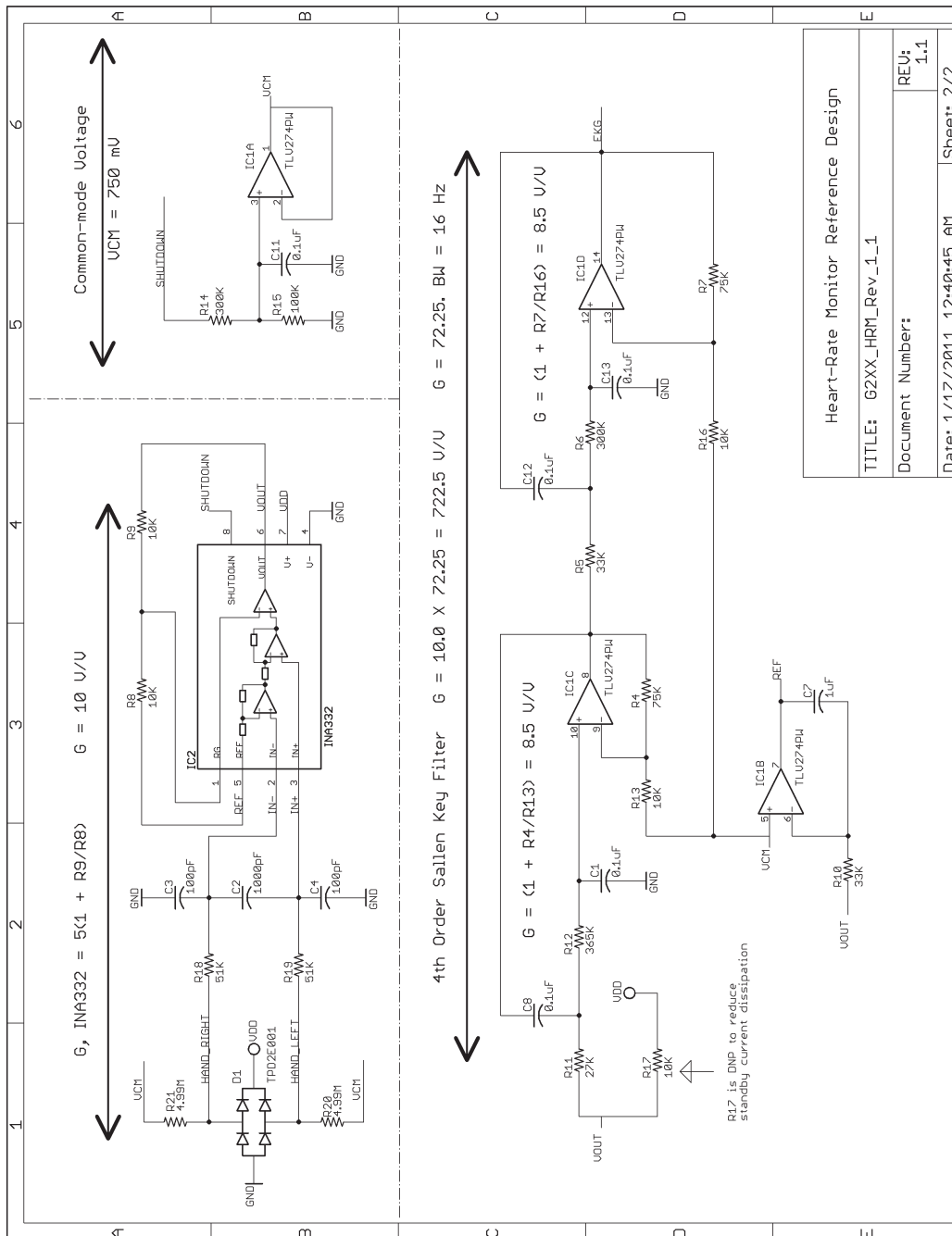


Figure 6. Hardware Schematic Diagram (Page 2/2)

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