EKG-Based Heart-Rate Monitor Implementation Using the MSP430G2xx LaunchPad™ Development Kit

Abhishek Joshi, Sourabh Ravindran, Austin Miller   *MSP430 System Solutions*

ABSTRACT

This application report describes a low-cost heart-rate monitor solution based on the MSP430G2 LaunchPad™ Development Kit, which supports the MSP430G2xx microcontrollers (MCUs). 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 kit. Additionally, an eZ430 radio frequency (RF) target can be connected to the six-pin header on the daughterboard to transmit data wirelessly using the SimpliciTI™ network protocol. The system can be powered by 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 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.
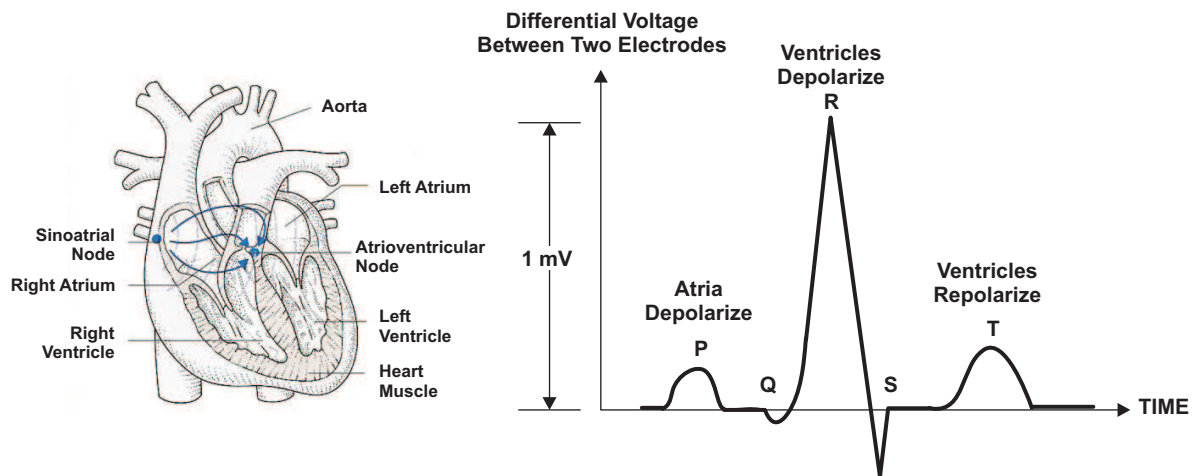

Figure 1. Human Heart Anatomy (left) and EKG Waveform (right)

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 through 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, and headers, while the MSP430 MCU, the back-channel UART, and the eZ430 emulator circuit with the USB connector reside on the LaunchPad kit 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 range of 100 kΩ to 300 kΩ, and the resistance placed between the conductive pads is significantly greater than this range, as Figure 2 shows.
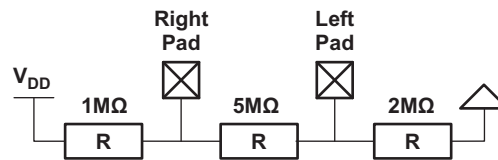

Figure 2. Hand Detection Circuit Diagram

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 μA, and shutdown current levels less than 1 μA. 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 *Heart-Rate and EKG Monitor Using the MSP430FG439*.

The INA332 is configured to a gain of 10 V/V with external 0.1% 10-kΩ resistors. The conductive pads are connected to the inputs with 51-kΩ resistors in series to limit the current from the human body and also act as a RC low-pass filter. The 5-MΩ pulldown resistors from the pads to common-mode voltage (V$_{CM}$) help keep the voltage identical on both inputs and also provide a DC bias point for circuit operation. The V$_{CM}$ 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 μA/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 X 8.5 X 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* .

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 Pin Functionality Mapping on the LaunchPad Kit

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 MCU was used for this application and has 8KB of flash, 256 bytes of RAM, a Timer_A3, and an 8-channel ADC10 [10]. The pin mapping on the LaunchPad kit is designed to match the pinout of the MSP430G2xx family of devices.

Table 1 and Table 2 show the pin functionality mapping for the left and right header pins, respectively, on the LanchPad kit.

Table 1. Pin Functionality Mapping – Left Header

Port or 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. Pin Functionality Mapping – Right Header

Port or Pin Name	Signal Name	Description
GND	GND	Ground (GND) for the MSP430
XIN	P2_6	V_{DD} for hand detection circuit
XOUT	SHUTDOWN	Enable or 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 kit. 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 kit, 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 kit (V$_{CC}$, RXD, TXD, TEST, RST).
2. Remove the jumper JP1 on the daughterboard.
3. Connect the micro-USB cable from the LaunchPad kit 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 an application UART connection between the PC and the LaunchPad kit [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 kit 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 or AAA batteries.

> ## WARNING
>
> **When powering the system from batteries, either the coin-cell or the 2 AA or 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 μA

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

3   Software

Figure 3 shows the flow chart for this application software.
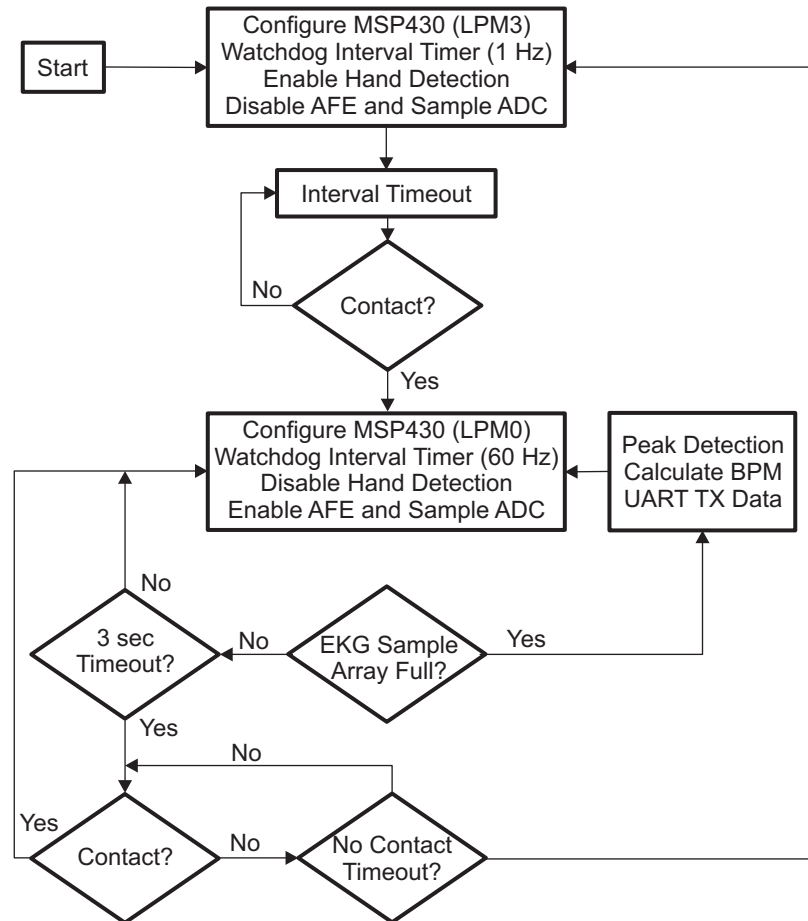

Figure 3. Software Flowchart

It begins by initializing the MSP430 in LPM3 sleep mode, configuring the watchdog timer in interval-timer mode (sourced by ACLK or 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 kit 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 MCU enters 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 the 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 using a Timer_A based UART. The UART output can be relayed to the PC by means of either the back-channel UART-over-USB connection on the LaunchPad kit or the eZ430 RF target header on the daughterboard. During the EKG sampling by the ADC, the hand-detection circuit is momentarily enabled every 3 seconds to ensure that contact is being made. If there is contact, the application returns to EKG sampling. If not, the hand-detection circuit remains enabled, and the applications checks for contact for approximately 10 seconds. If there is still no contact, the AFE is disabled and the MSP430 MCU returns back to the initial LPM3 state in which 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 in action (left side) and the UART output log display on the HyperTerminal application window on the PC (right side).
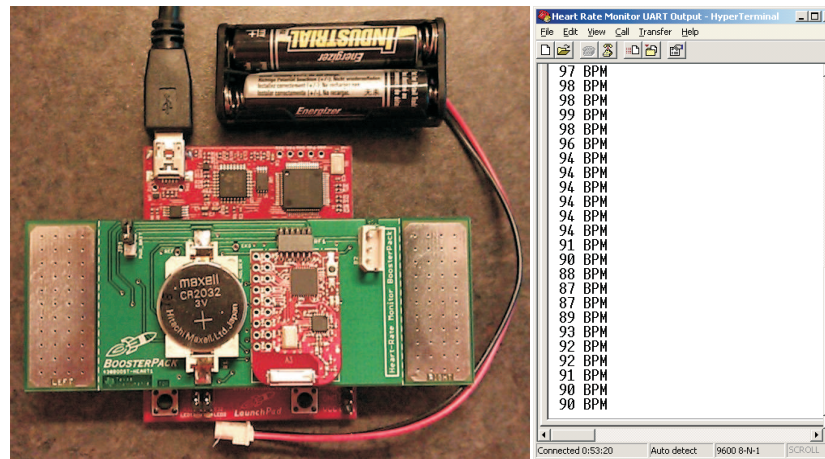

Figure 4. Heart-Rate Monitor Setup (left) and UART Output on PC (right)
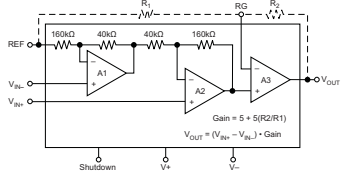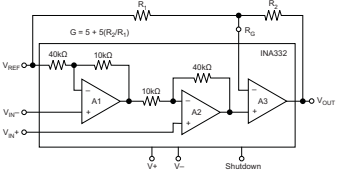
4   References
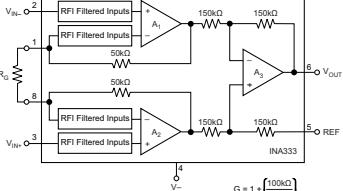
1. http://www.daviddarling.info/images/sinoatrial_node.jpg
2. http://www.medterms.com
3. *Heart-Rate and EKG Monitor Using the MSP430FG439*
4. *MSP-EXP430G2 LaunchPad Development Kit User's Guide*
5. *eZ430-RF2500 Development Tool User's Guide*
6. A2500R24A-EZ4x - Integrated Radio (AIR) EZ4x Module Series 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*
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.
10. *MSP430G2x52, MSP430Gx12 Mixed-Signal Microcontrollers data sheet*

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.

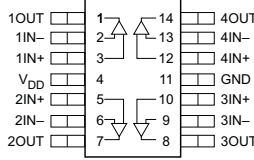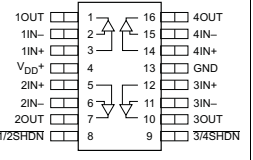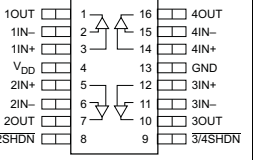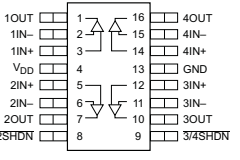**Table 4. Instrumentation Amplifier Comparison**

Device Name	INA321	INA332	INA333
Quiescent current	40 µA/channel	490 µA/channel	50 µA/channel
Shutdown current	<1 µA	approximately 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 to 5.5 V	2.7 V to 5.5 V	1.8 V to 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	TLV2765
Supply current	470 μA/channel (V_{DD} = 2.7 V)	470 μA/channel (V_{DD} = 2.7 V)	20 μA/channel	650 μA/channel
Shutdown current	No shutdown	approximately 25 μA	approximately 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	2.1 V/μs (V_{DD} = 2.7V)	2 V/μs (V_{DD} = 2.7 V)	0.2 V/μs (V_{DD} = 2.4 V)	4.8 V/μs (V_{DD} = 2.7 V)
Supply voltage	2.7 V to 16 V	2.7 V to 16 V	1.8 V to 3.6 V	1.8 V to 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.

Wired USB Demo With Back-Channel UART

The default setup for the heart-rate monitor uses the onboard emulator circuit on the LaunchPad kit 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 kit (V_{CC}, RXD, TXD, TEST, RST).
2. Remove the jumper JP1 on the daughterboard.
3. Attach the daughterboard to the LaunchPad kit.
4. Connect the mini-USB cable from the LaunchPad kit 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™ IDE v5.10 and Code Composer Studio™ IDE v4.2.1.

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 with 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.

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 with the Spy-Bi-Wire (2-wire JTAG) protocol. For more details on the hardware specifications, see the *eZ430-RF2500 Development Tool User's Guide*.

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 IDE v5.10 and Code Composer Studio IDE v4.2.1. 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 4KB 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 through the 6-pin connector, as previously mentioned) receives data through UART (9600 baud) and transmits it using 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 using the SimpliciTI protocol from the end point. It then outputs that data through the 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 predefined 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.
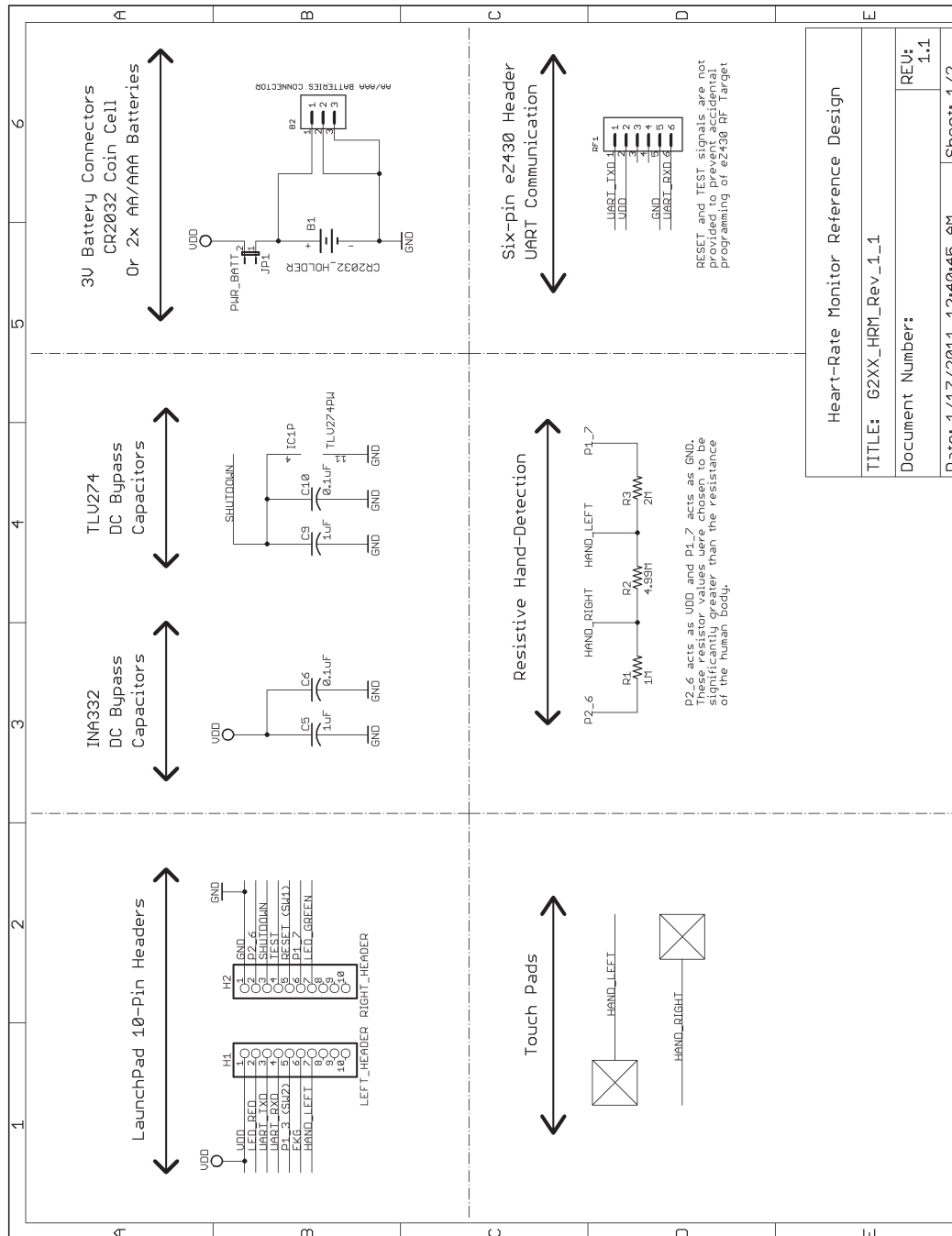
Hardware Schematic Diagrams

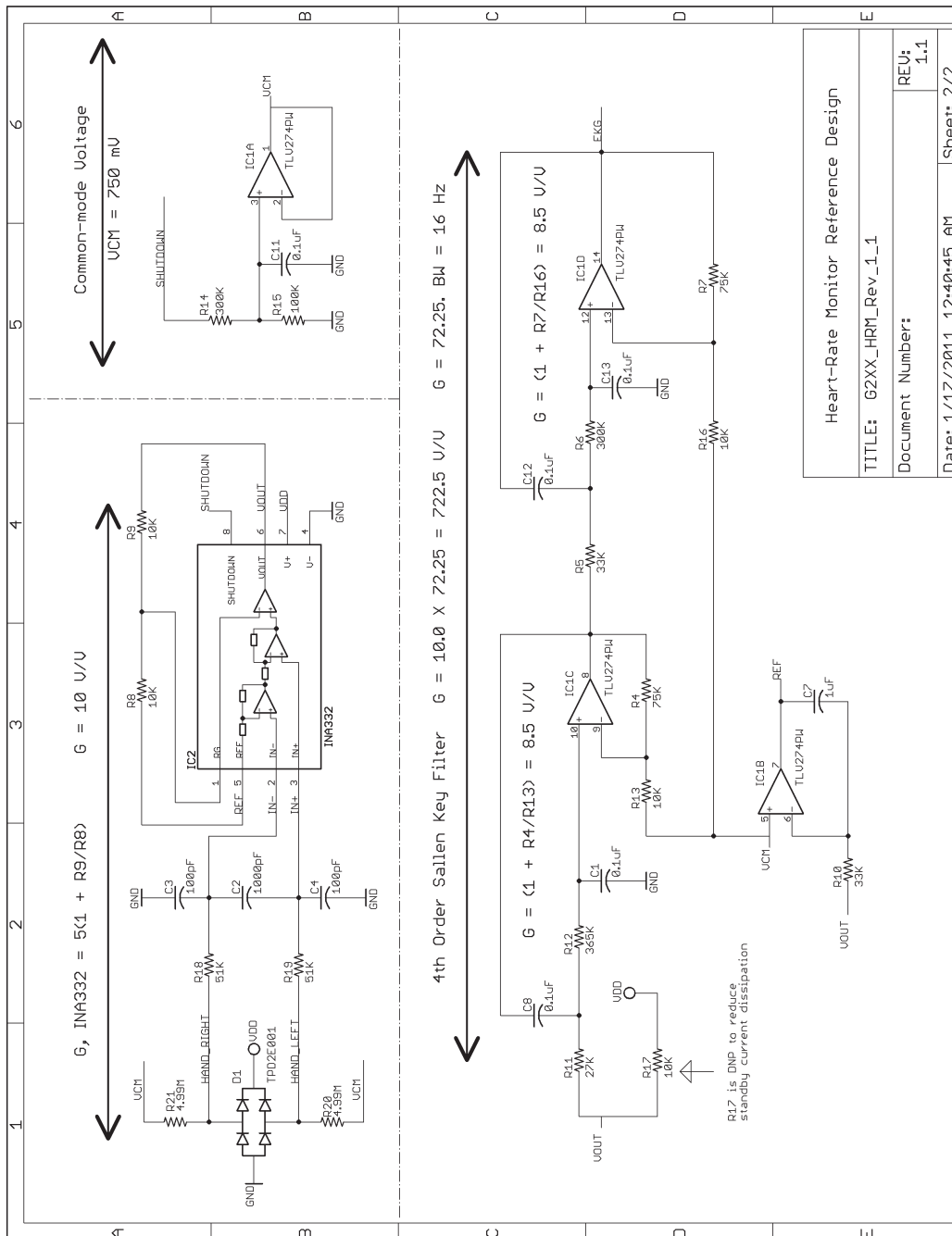**Figure 5. Hardware Schematic Diagram (Page 1 of 2)**

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

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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