Wrist based HRM Reference Design

TI Reference Designs

TI Reference Designs are mixed-signal solutions created by TI's experts. Verified Designs offer the theory, complete PCB schematic & layout, bill of materials and measured performance of the overall system.

Circuit Description

The Heart Rate Monitor (HRM) is an electronic device that detects physiological parameters and converts to usable heart rate reading. Heart rate is the number of times the heart beats in a minute and it is produced via depolarization at the sinoatrial and atrioventricular nodes in the heart. A basic HRM is comprised of a sensing probe attached to a patient's earlobe, toe, finger or other body locations, depending upon the sensing method (reflection or transmission), and a data acquisition system for the calculation and eventually display of the heart rate.

This reference design discusses the methodology for achieving a Low Power, Portable, Low-End Reflectance mode Wrist based HRM.

The design employs reflectance mode photoplethysmography (PPG) to extract the pulse signal from the wrist which is equivalent to the heart beat.

High Performance is achieved by using the AFE4400, a Fully Integrated Analog Front End that consists of a low noise receiver channel with an integrated Analog to Digital Converter, an LED transmit section, diagnostics for sensor and LED fault detection.

Additional components are an ultra-low power microcontroller (MCU) for calculating the heart rate, a wireless module based on Bluetooth Low Energy (BLE) for exchanging information with smart phones, tablets or PCs, a motion sensor for monitoring the user's activity, a reflectance mode sensing probe, ferroelectric RAM (FRAM) for data logging, a lithium-polymer rechargeable battery, a battery charger and a battery fuel gauge.
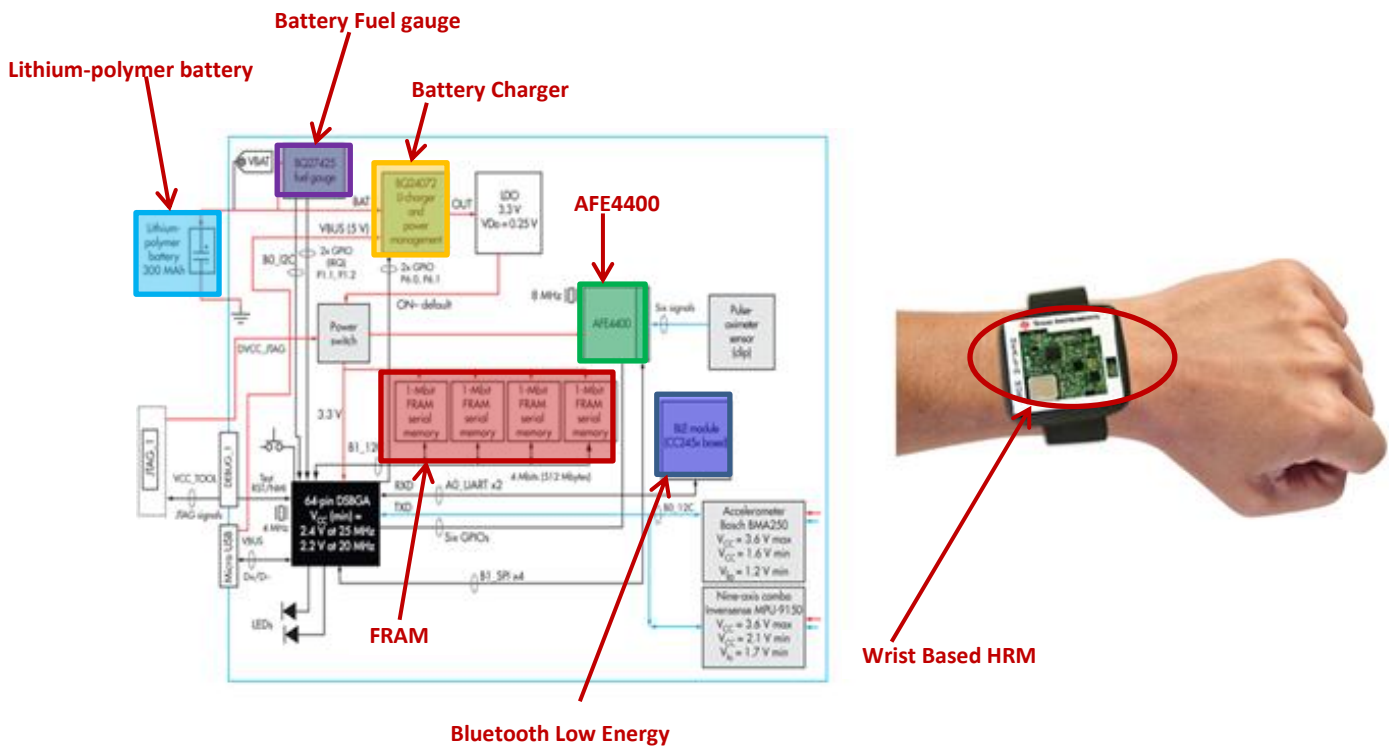
Design Resources

Design Archive (ZIP File)   All design files
         Product Folder

1. Design Summary

This design takes a block level approach for designing a low power wrist based HRM.

1.1 Design Goal

Provide a Reflectance mode Wrist based HRM reference example.

2. Theory of Operation

2.1 Background on HR Measurements

To facilitate plethysmography measurement, three sensing mechanisms are commonly used, namely, volume displacement plethysmography, impedance plethysmography, and photoplethysmography. The photoplethysmography (PPG) is preferred in our design because measurement can be performed on the wrist without precise positioning. Additionally, the design can easily upgrade to blood oxygen saturation measurement.

Photoplethysmography (PPG) is based on plethysmography and photovoltaic technique, as displayed in Figure 1 (a).
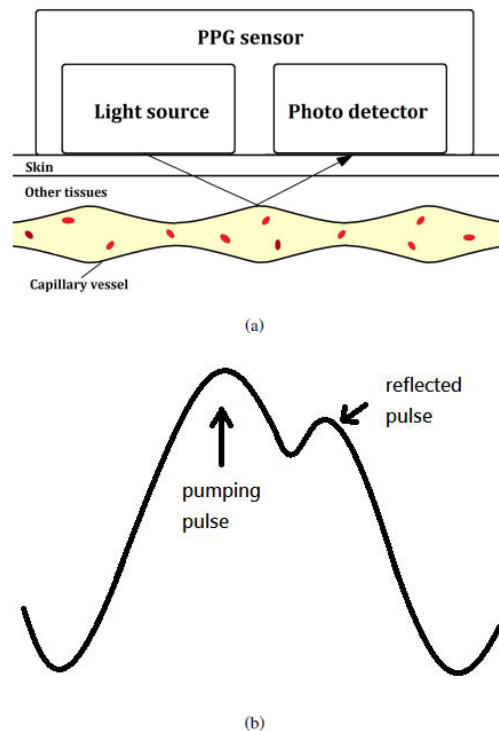

Figure 1 (a) Basic PPG technique; (b) Sample PPG waveform

Every time when blood pumps to periphery (ejection phase), blood vessels expand due to the blood pressure from the heart, a pulse will be generated. And every time when the blood flows back (diastolic filling phase), another pulse follows. So the PPG signal will be the superposition of the pumping pulse and the reflected wave, as shown in Figure 1(b).
Implementing a suitable algorithm it's possible to extract the heart beat information from the PPG signal.

2.2 Hardware overview and circuit description

The key components required for acquiring and signal-conditioning the PPG signals are the LED, photodetector and AFE.
Some commercially available AFEs, like TI's AFE4400, integrate both the LED driver circuitry and the photodiode signal conditioning circuitry in a single package, Figure 2. This new generation of AFEs can drive the LED currents in using an H-bridge configuration capable of driving up to 150 mA/leg, with short-circuit protection. They can also increase the dynamic range greater than 105 dB and create a current reference independent of the IR and red LEDs.
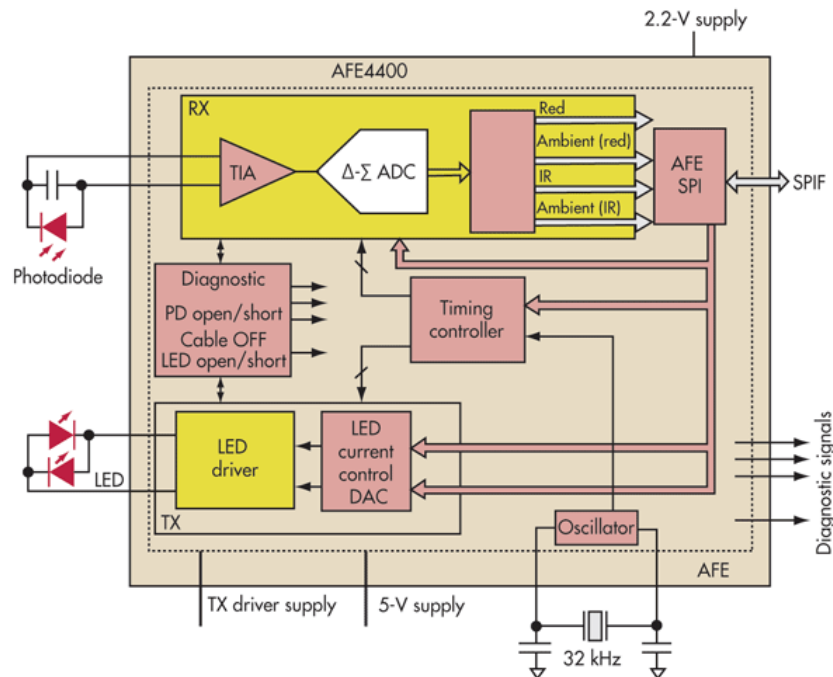

Figure 2 Commercially available AFEs like TI's AFE4400 integrate the LED driver circuitry and the photodiode signal conditioning circuitry in a single package

The photodiode circuitry embedded into these devices can amplify currents below 1 µA with 13 bits of resolution. It is ultra-low-power (<4 mW) and has a programmable TIA. The AFE consumes less than 3 mA of current when active.

2.2.1 LED Transmit Section

As highlighted in Figure 3, the transmit stage contains two sections: the LED driver and LED current control section.

   a. **LED Driver** - There are two LEDs, one for the visible red wavelength and another for the infrared wave length. To turn them on, an H-Bridge circuit is used. The LED1_ON and LED2_ON signal decide which LED to turn on (the whole circuit is time multiplexed).
   b. **LED Current Control** – The current source (I_{LED}) locally regulates and ensures that the actual LED current tracks the specified reference. The LED1 and LED2 reference current can be independently set by Register. The 8-bit current resolution here meets a dynamic range of better than 105dB (based on a 1-sigma LED current noise).

c. **A Push**-Pull LED driver is also supported, please refer to AFE4400 Datasheet for detail.
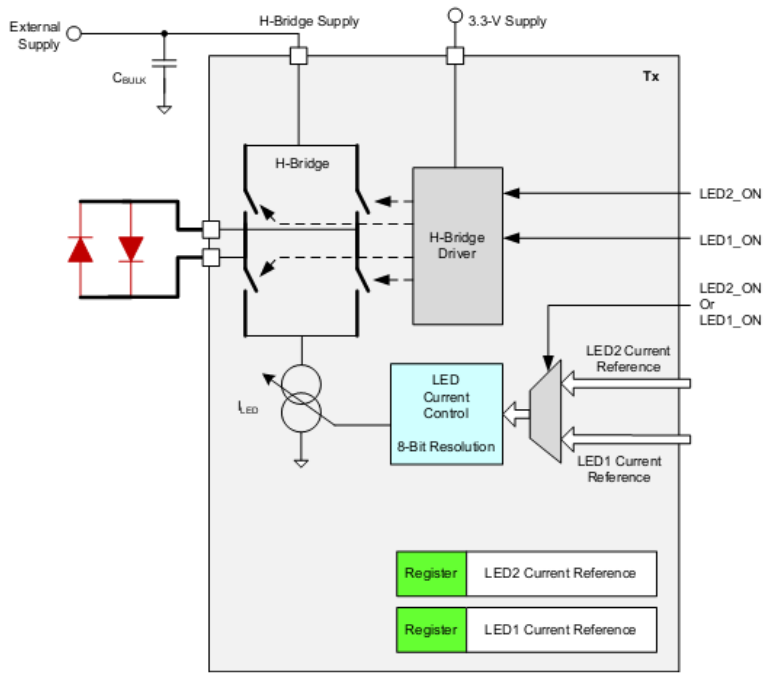

Figure 3 LED Transmit Section

2.2.2 Receiver Stage

2.2.2.1 I-V Amplifier (Transimpedance Amplifier) and Ambient Cancellation Section
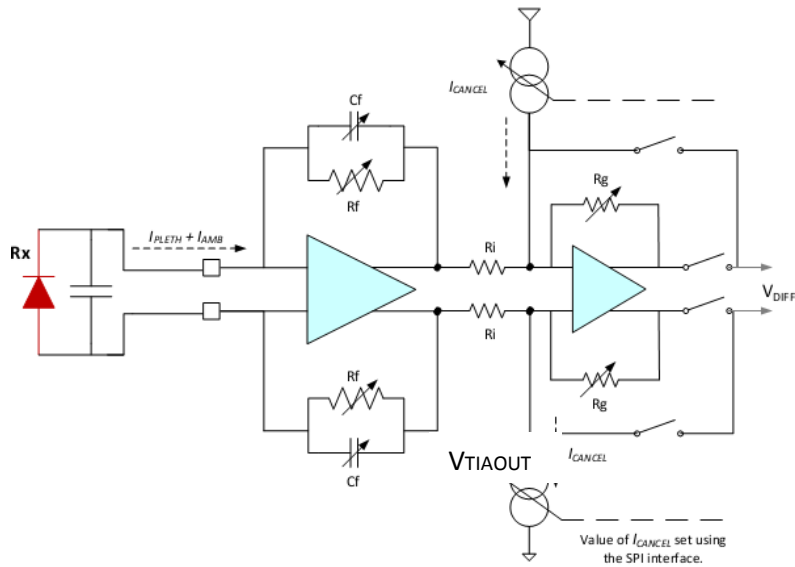

Figure 4 Receiver Section – Stage 1

The RX Stage consists of a differential current-to –voltage transimpedance amplifier that converts the input photodiode current into an appropriated voltage, as shown in Figure 4. The feedback resistor of the amplifier (R_f) is programmable to support a wide range of photodiodes currents. (Available values in AFE4400: 1MΩ, 500kΩ, 250kΩ, 100kΩ, 50kΩ, 25kΩ, and 10kΩ)

The differential voltage at the TIA output includes the pleth component (the desired signal) and a component resulting from the ambient light leakage:

$$V_{TIAOUT} = 2 * (I_{PLETH} + I_{AMB}) * R_f$$

The feedback resistor R_f and feedback capacitor C_f form a low-pass filter for the input signal current. Always ensure that the low-pass filter has sufficiently high bandwidth (as shown by Equation below) because the input current consists of pulses. For this reason, the feedback capacitor is also programmable. (Available value include: 5pF, 10pF, 25pF, 50pF, 100pF and 250pF. Any combination of these capacitors can also be used)

The TIA is followed by the second stage, which consists of a current digital-to-analog converter (DAC) that sources the cancellation current and an amplifier that gains up the pleth component alone. The current DAC (I_{CANCEL}) has a cancellation current range of 10 uA with 10 steps (1 uA each). The amplifier has five programmable gain settings (Rg/R_i): 1, 1.414, 2, 2.828 and 4.

The receiver provides digital samples corresponding to ambient duration. The host processor can use these ambient values to estimate the amount of ambient light leakage. The processor must then set the value of the ambient cancellation DAC. Using the set value, the ambient cancellation stage subtracts the ambient component and gains up only the pleth component of the received signal.

The differential output of the second stage is V_{DIFF}:

$$V_{DIFF} = 2 * \left[I_{PLETH} * \frac{R_f}{R_i} + I_{AMB} * \frac{R_f}{R_i} - I_{CANCEL} \right] * R_g$$

Where：

R_i = 100kΩ,

I_{PLETH} = photodiode current pleth component,

I_{AMB} = photodiode current ambient component, and

I_{CANCEL} = the cancellation current DAC value (as estimated by the host processor).

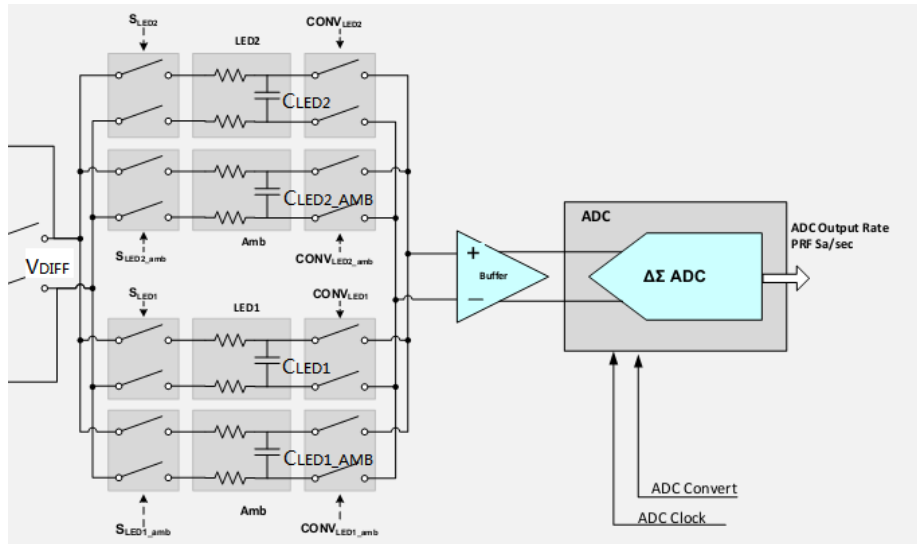## 2.2.2.2 Filter and Analog-to-Digital Converter

Figure 5 Receiver Section – Stage 2

The output of the ambient cancellation amplifier is separated into LED2 and LED1 channels.

1) When LED2 is on, the amplifier output is filtered and sampled on capacitor C_{LED2},
2) When LED1 is on, the amplifier output is filtered and sampled on capacitor C_{LED1},
3) In between the LED2 and LED1 pulses, the idle amplifier output is sampled to estimate the ambient signal on capacitors C_{LED2_AMB} and C_{LED1_AMB}.

The sampling duration is termed the Rx sample time and is programmable for each signal, independently. The sampling can start after the I-V amplifier output is stable (to account for LED and cable settling times). The Rx sample time is used for all dynamic range calculations; the minimum time supported is 50μs.

A single, 22-bit ADC converts the sampled LED2, LED1, and ambient signals sequentially. Each conversion takes 25% of the pulse repetition period and provides a single digital code at the ADC output. Note that four data streams are available at the ADC output (LED2, LED1, ambient LED2, and ambient LED1) at the same rate as the pulse repetition frequency. The ADC is followed by a digital ambient subtraction block that additionally outputs the (LED2–ambientLED2) and (LED1–ambient LED1) data values.

2.2.2.3 Diagnostics

The device includes diagnostics to detect open or short conditions of the LED and photo sensor, LED current profile feedback, and cable on or off detection. By default, the diagnostic function takes tDIAG = 8 ms to complete after the DIAG_EN register bit is enabled. The diagnostics module, when enabled, checks for nine types of faults sequentially. The faults are listed below:

2.2.2.4 Photodiode-Side Fault Detection

Figure 9 shows the diagnostic for the photodiode-side fault detection.
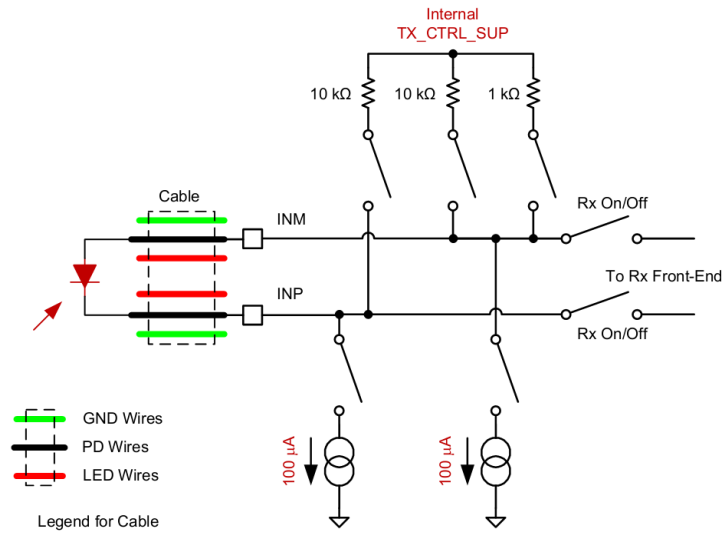
Figure 6 Photodiode Side Fault Detection

2.2.2.5 Transmitter-Side Fault Detection

Figure 10 shows the diagnostic for the photodiode-side fault detection.
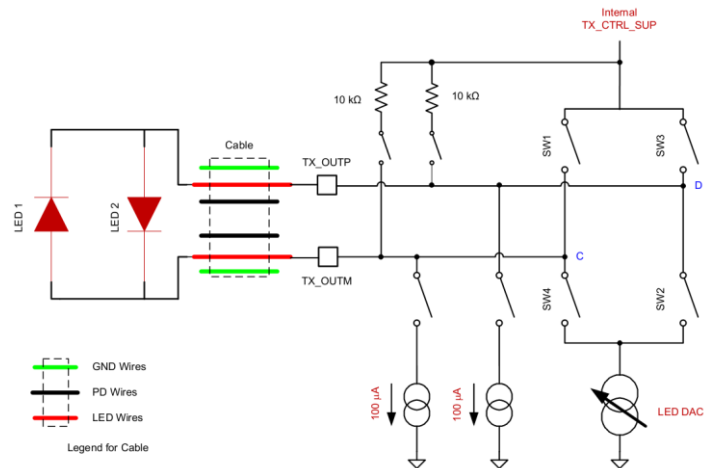
Figure 7 Transmitter Fault Detection

2.3 Microcontroller

In this design example, the microcontroller is used to calculate the heart rate, merge the motion sensor data, and process the AFE information. The microcontroller should have specific features including the ability to maintain the context at all times. It should also have a limited power budget because it will be continuously running and nobody wants to drain the batteries.

2.4 Motion Sensors

Sensors are a fundamental part of the human machine interface (HMI). They help the system identify the context and environmental conditions. Motion sensors such as accelerometers, gyroscopes, and magnetometers help identify whether a person is seated, walking, or running. They are key elements to identify the orientation of the arm, wrist, or other specific part of the body where the activity monitor is located.
They also help to track the travel distances and provide a more accurate position of the system by increasing the resolution of the GPS with dead-reckoning algorithms.

2.5 Communication Link

The system described in this article has both wireless and wired communication links. The wireless communication link is based on BLE and is based on the BR-LE4.0-S2A, an FCC-certified (Federal Communications Commission) system-in-PCB (printed-circuit board) module available online that only requires a few external components.
This module works with AT-based commands and is easy to use since it includes a network processor that handles all the transactions required by the Bluetooth 4.0 stack. The wired communication is based on USB 2.0. The microcontroller's built-in module requires only a few external components. USB is also used for charging the lithium-polymer battery.

2.6 Battery Charger and Fuel Gauge

The battery charger operates from either a USB port or ac adapter and supports charge currents up to 1.5 A. The input voltage range with input overvoltage protection supports unregulated adapters. The USB input current limit accuracy and startup sequence allow the battery charger to meet the USB-IF inrush current specification. Additionally, the input dynamic power management prevents the charger from crashing incorrectly configured USB sources.
The battery fuel gauge circuits an easy-to-configure microcontroller peripheral that provides system-side fuel gauging for single-cell lithium-ion batteries. The device requires minimal user configuration and system microcontroller firmware development. The battery fuel gauge uses the impedance track algorithm for fuel gauging and provides information such as remaining battery capacity (mAh), state-of-charge (%), and battery voltage (mV).

3. Verification and measured performance

3.1 Health Hub Demonstration Suite

The figure below shows up the Health Hub measurement setup hardware description. The app requires a PC, a BlueRadios USB Serial Dongle along with the wrist watch data acquisition system. The pictured device connects to the app via Bluetooth low energy.
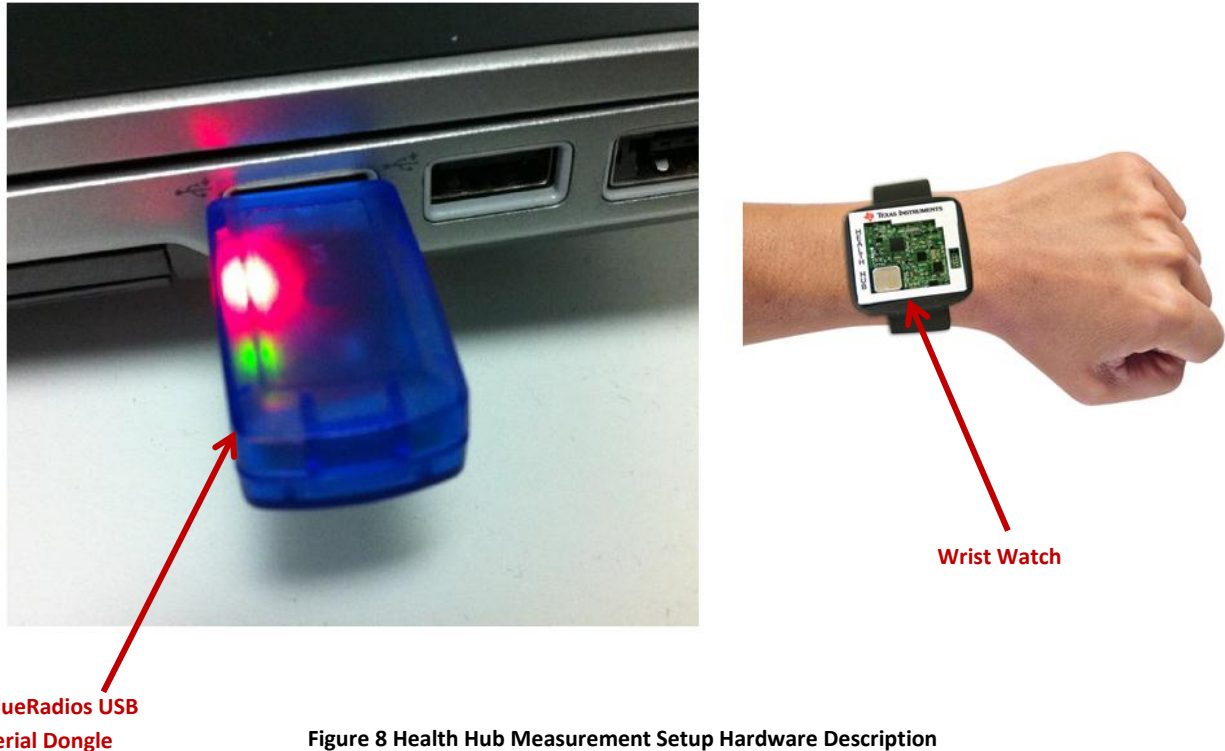

Wrist Watch

BlueRadios USB Serial Dongle

Figure 8 Health Hub Measurement Setup Hardware Description

3.2 Health Hub App

3.2.1 Interface Overview

Health Hub is designed to allow the control and display of many BLE enabled health monitoring devices on a single screen. The screen is divided into multiple discrete areas, Figure 9, called Device Controls and each area allows a specific BLE enabled health monitoring device control.

3.3 Demonstration usage

Terminology:

Advertising mode: the Bluetooth radio is broadcasting advertising data; this allows another device to initiate a connection to the advertising device.

Device: a piece of hardware required for a demo.

Device control: The area on the screen of the app that controls a device.
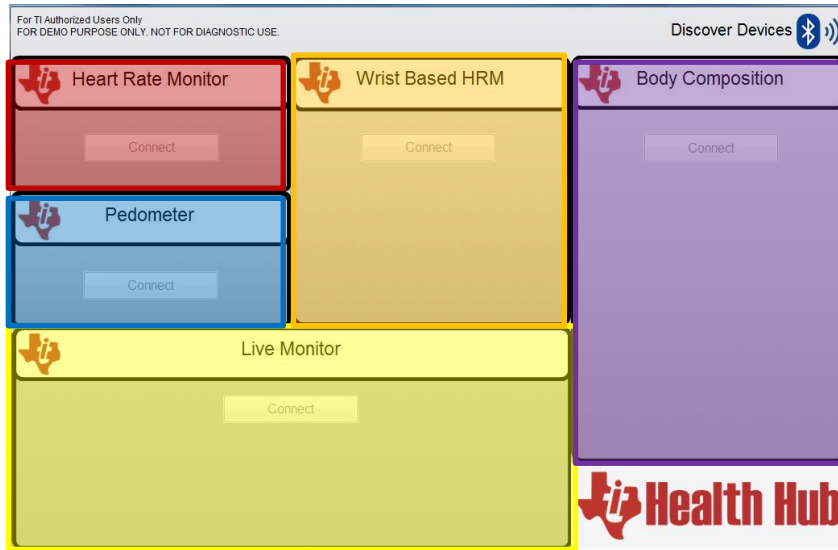
Figure 9 Health Hub PC GUI Interface with highlighted Device Controls

3.3.1 Common Operations

Common operations apply to all of the demos with the Health Hub app.

3.3.1.1 Find Devices

The first step in initiating a connection to a Health Hub demonstration device is to have the PC finding the device. To this end, the desired device must be in advertising mode. Generally the devices will advertise any time they are turned on and not connected. When the HRM is in advertising mode the green LED D7 on the wrist watch will be flashing. To find a device press the Discover Devices button as shown in the figure below. The icon will change to discovering and will find devices for about ten seconds.
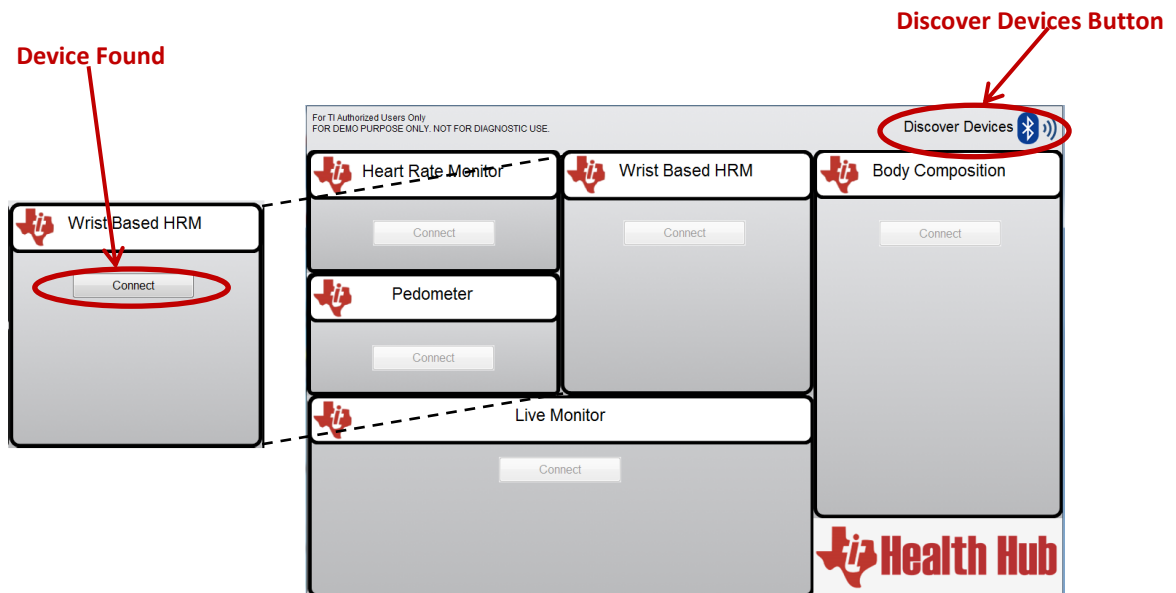
Figure 10 PC GUI front panel before and after searching for BLE enabled health monitoring devices

3.3.1.2 Connection

The second step is to form a connection. Before finding a device by using Discover Devices the device controls appear as in the figure below.

Figure 11 BLE enabled device not found

After a device has been found the device control will appear as in the figure below.

Figure 12 Device found – connection can be established

When the Connect button is pressed a selector will be shown as below

Figure 13 Desired Device selection from the list

When the desired device is selected from the list, the app will form a connection to the device over Bluetooth low energy. After connection the device control will open fully and control over the device can begin. The solid blue LED labeled D8 indicates the connected state. When the device is reporting periodic data, the blue LED labeled D2 will flash. Periodic data only is used with the Wrist Based HRM device control. When the device is reporting graphic data, the green LED labeled D1 will be on. Live Monitor uses both periodic and graphic data.

NOTE if after selecting a device from the selector the device control becomes unavailable, an immediate disconnect has occurred. If this happens repeatedly the devices batteries may be depleted.

3.4 Measured Results

The device should be worn tightly around the wrist. The device is sensitive to motion. The quality of the output data is highly dependent on the stillness of the user's arm and placement of the sensor. The effect of motion can be visualized using the Live Monitor device control. The graph shown in the Wrist Based HRM device control is a history of the reported values.

Device Front

Device back
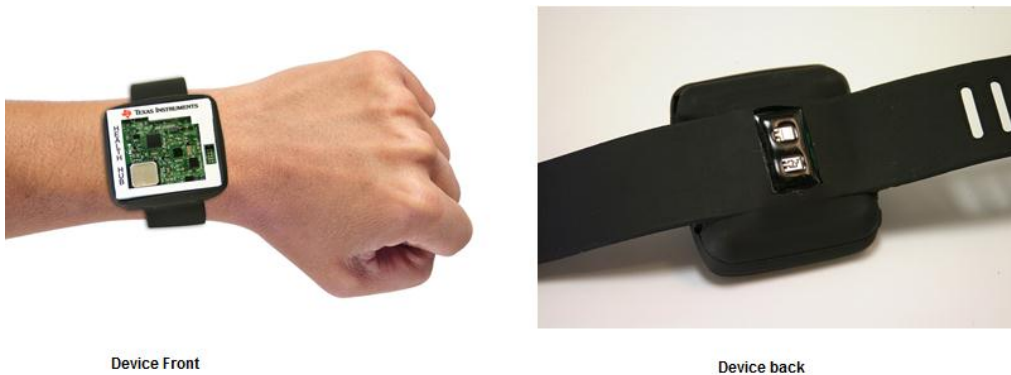
Figure 14 Wrist HRM measurement setup

The following figure shows up some measurement results
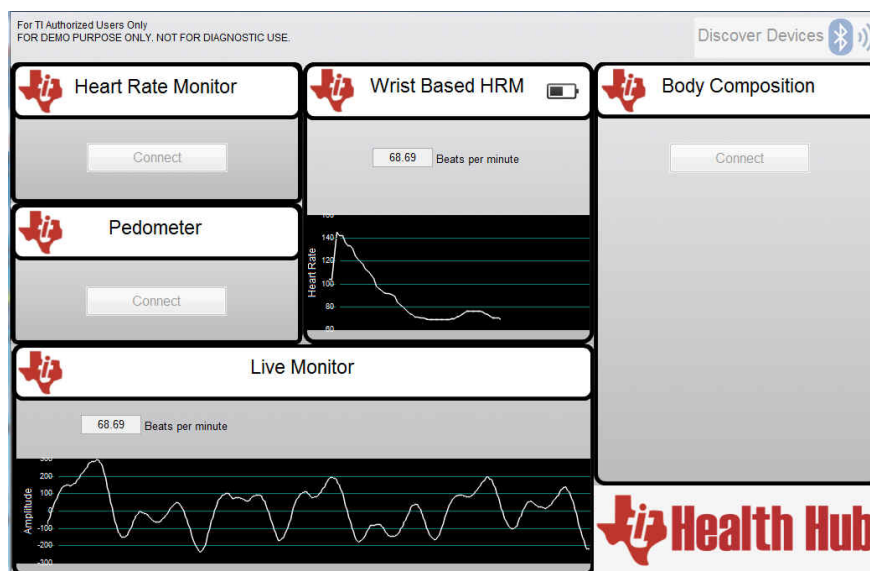
Figure 15 Measurement results

IMPORTANT NOTICE

Products		Applications	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		