Design Guide: TIDA-010266

Low-Cost Blood Pressure and Heart Rate Monitor Reference Design

Description

This is a reference design for a low-cost electronic blood pressure monitor (BPM), or sphygmomanometer, with focus on low-noise performance using both TI's Microcontroller (MCU)-integrated chopping amplifiers and small size external amplifiers. This design targets portable battery-operated devices and showcases how the MSPM0L1306 with integrated precision analog can be leveraged to reduce cost and external components. The designer can easily switch to the included INA350 to evaluate alternative low-cost architectures, and test TI's smallest motor and pump driver, the DRV8210. A GUI is included for testing and evaluation.

Resources

TIDA-010266	Design Folder
MSPM0L1306	Product Folder
LMV324A	Product Folder
INA350	Product Folder
DRV8210	Product Folder
TPS7A24	Product Folder

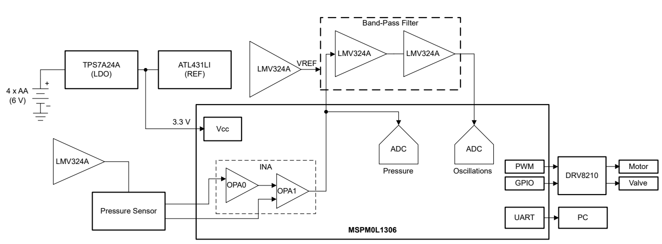
Ask our TI E2E™ support experts

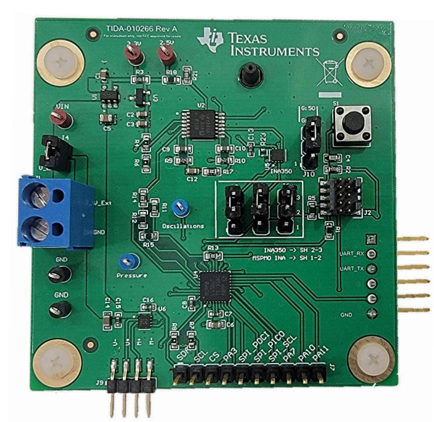
Features

- Ultra-low-power in standby mode for extended battery life
- Low-cost MCU with integrated INA for size and BOM reductions
- Supports GUI and Raw Data Readout for ease of algorithm development and post-processing
- Smallest integrated valve and pump driver design helps in reducing the overall size
- On-the-fly transition for evaluation of both external INA and MCU-integrated INA

Applications

- Blood pressure monitor
- Multiparameter patient monitor





1 System Description

This design is a reference design for an electronic sphygmomanometer that can log systolic, diastolic, and heart-rate data through one measurement. This design collects data from a cuff tied to the upper arm and then processes these data. Two signal-conditioning options are provided for evaluation. A two-amplifier INA through the integrated operational amplifiers inside the MSPM0L1306 followed by a two-stage band-pass filter, or the INA350 followed by the band-pass filter. The systolic pressure, diastolic pressure, and heart rate can be extracted from the raw pressure and oscillations data through the use of different algorithms. The measured results are then sent through universal asynchronous receiver/transmitter (UART) to TI's blood pressure monitor GUI for evaluation.

1.1 Terminology

Systole The contraction of the heart by which the blood is forced out of the chambers and into the aorta and pulmonary artery. The first number in a blood pressure reading is called *systolic* blood pressure. Systolic blood pressure measures the pressure in the arteries when the heart beats.

Diastole The relaxation and dilation of the chambers of the heart and especially the ventricles during which the chambers fill with blood. The second number in a blood pressure reading is called *diastolic* blood pressure. Diastolic blood pressure measures the pressure in the arteries when the heart rests between beats.

INA Instrumentation amplifier

1.2 Key System Specifications

PARAMETER	SPECIFICATION	DETAILS
System Battery	6-V DC power	Four 1.5-V AA batteries
Pressure Sensor	**Drive Current**: 100 µA **Pressure range**: –50 kPa to 50 kPa **Bridge resistance:** 20 kΩ	2SMPP-03
DC Air Pump	Rated voltage: 6-V rated current: < 430 mA **Diameter of air tap**: 4.3 mm	
DC Air Valve	Rated voltage: 6-V normal open type **Diameter of air tap**: 3 mm	

2 System Overview

2.1 Block Diagram

Figure 2-1 and Figure 2-2 shows the block diagram variants A and B.

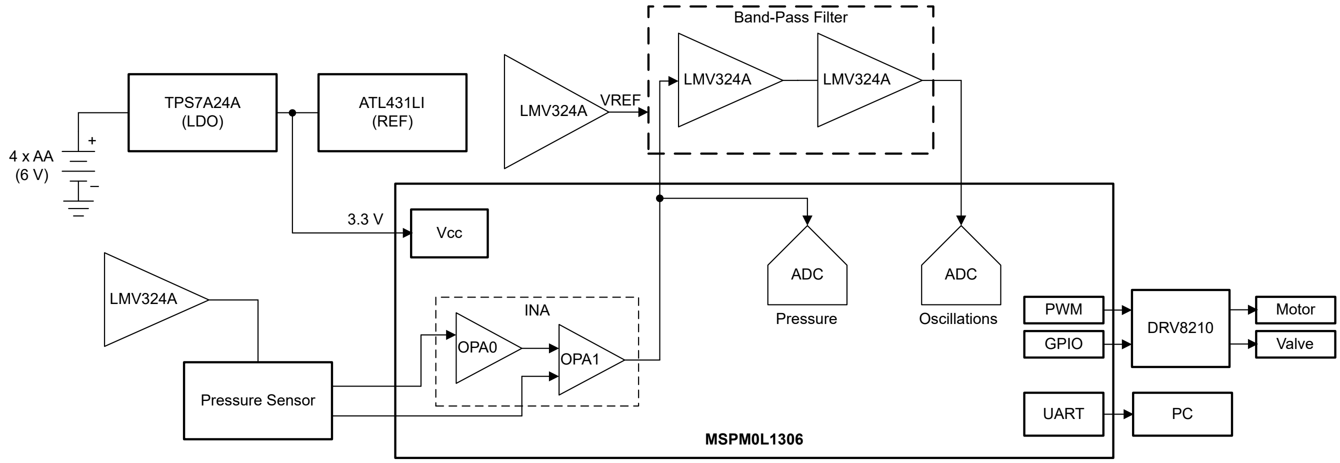


Figure 2-1. System Block Diagram A

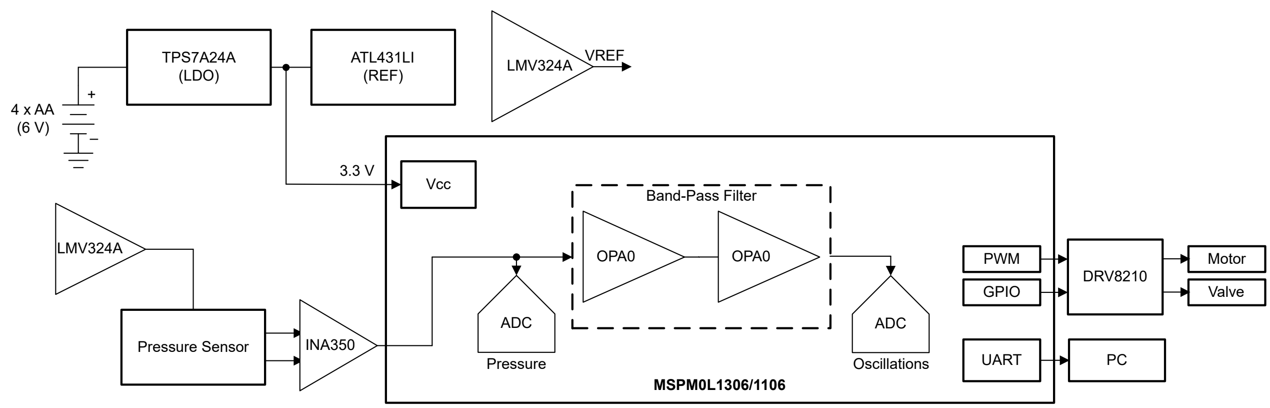


Figure 2-2. System Block Diagram B

2.2 Design Considerations

Blood pressure is an important physiological parameter of the human body that carries a lot of physiological and pathological information. The two basic methods to get blood pressure are the Korotkoff Sounds method and the oscillography method.

To use the blood pressure monitor, do as follows:

1. Tie the cuff to the upper arm of the subject
2. Inflate the cuff slowly to constrict the arm
3. Measure pressure as the cuff deflates

2.2.1 System Design Theory

Blood flows into the arm and creates pressure in the blood vessel; the blood flow changes with the heart rate and creates a periodic waveform. The blood flow is blocked when the pressure of the cuff is greater than systolic; after the blood flow is blocked, the waveform disappears. During the measuring period, the pressure data from the sensor is the superposition of static pressure from the cuff and the oscillation wave from the vessel. The oscillation wave becomes larger with the further increase of pressure in the cuff. After reaching the maximum value, the oscillation wave lessens; after the blood vessel is blocked, the oscillation wave disappears. The pressure of the cuff is called average pressure where the oscillation wave has the maximum value (see Figure 2-3).

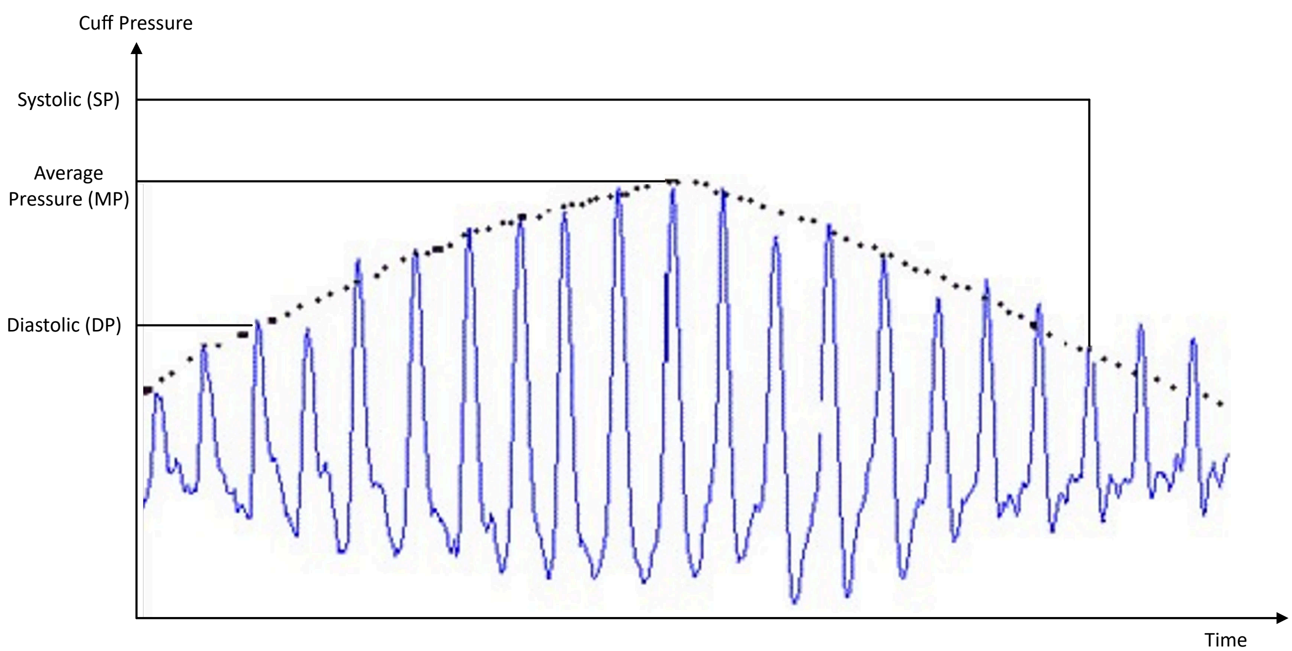


Figure 2-3. Oscillation Method to Get Blood Pressure

Obtaining the oscillation wave and the envelop is easy (see Figure 2-3), but systolic and diastolic parameters are required. There are two methods get these parameters from the oscillation curve. One method is called the proportionality coefficient method, where a proportional relationship exists between average pressure and systolic and diastolic (the coefficients are called Ks and Kd, respectively).

$$\frac{SP}{MP} = Ks\ (\text{value range: } 0.30 - 0.75) \quad (1)$$

$$\frac{DP}{MP} = Kd\ (\text{value range: } 0.45 - 0.90) \quad (2)$$

These two coefficients are obtained from a large number of statistical data. The proportionality coefficient method is simple and suitable for MCU applications, but the difference between individuals is large and inconsistent. Sometimes large errors occur with this method.

Many other algorithms and approaches are available, and provide trade-offs between power consumption and processor requirements. The proportionality coefficients (Ks, Kd) are listed in Table 2-1 for reference only. The included software leaves the blood pressure algorithm section blank.

Table 2-1. Ks, Kd Value According to Average Pressure Range (J Moraes)

AVERAGE PRESSURE RANGE (mmHg)	Ks	AVERAGE PRESSURE RANGE (mmHg)	Kd
MAP > 200	0.5	MAP > 180	0.75
200 ≥ MAP > 150	0.29	180 ≥ MAP > 140	0.82
150 ≥ MAP > 135	0.45	140 ≥ MAP > 120	0.85
135 ≥ MAP > 120	0.52	120 ≥ MAP > 60	0.78
120 ≥ MAP > 110	0.57	60 ≥ MAP > 50	0.6
110 ≥ MAP > 70	0.58	50 ≥ MAP	0.5
70 ≥ MAP	0.64	50 ≥ MAP	0.5

This design utilizes the Omron 2SMPP-03 pressure sensor, which provides approximately a 0-mV to 30-mV output voltage range across the 0-kPa to 40-kPa pressure range of interest for this application. This is a 20-kΩ piezoresistive bridge sensor biased with 100 µA. This bridge was selected for the low power consumption. Although signal-to-noise ratio (SNR) is typically given up to extend battery life, this low-cost signal chain can achieve < 10 μV_{PP} of input-referred noise, which enables increasing the gain of the signal chain and reducing the current required to drive the pressure bridge.

2.2.2 Bridge Biasing

In this implementation, a constant 100 µA is achieved by fixing a constant 0.249 V across a 0.1% tolerant 2.49-kΩ resistor. Figure 2-4 shows one of the four available amplifiers in the LMV324A used for this purpose. Rail-to-rail output is needed for increasing the driving current and maintaining voltage headroom at lower supply voltage.

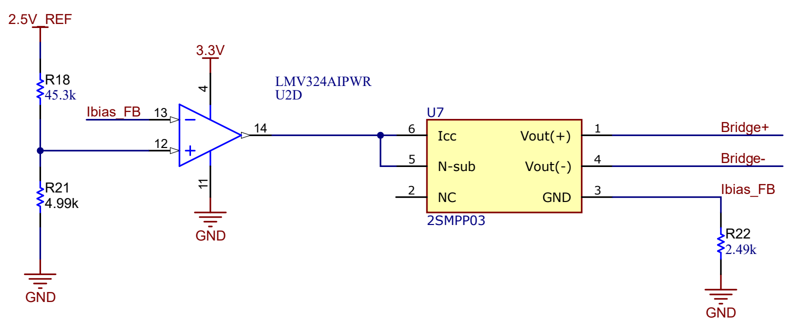


Figure 2-4. Pressure Sensor Biasing Circuit

2.2.3 INA Stage

This reference design allows for two different INA implementations to be used for evaluation. The first one, seen in Figure 2-1, uses the integrated amplifiers of the MSPM0 to form a two amplifier INA with approximately 32 dB of gain as shown in Figure 2-5. For detailed steps of the design process, see the *Overcurrent event detection circuit* design guide.

Figure 2-2 illustrates the second implementation using the low-cost integrated INA350 with a 3.5-μV_{PP}, 1/f noise and gain settings of 20 V/V or 50 V/V through a gain select pin. The low-cost INA350 or INA351A can be paired with a lower cost MSPM0L1106 if the extra amplifiers are not needed.

At this point, the blood vessel oscillations (0.5 Hz–7 Hz) caused by the heart pumping blood in the order of 100-µV to 300-µV peak-to-peak amplitude, are superimposed on a 15-mV amplitude DC signal going into the INA. The expected output is 750-mV DC pressure range with about 10-mV oscillations.

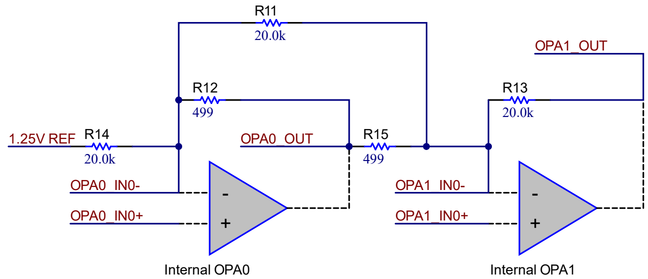


Figure 2-5. Two-Amplifier INA Circuit

2.2.4 Filter Design

The filter design for this application has the challenge of requiring a low-noise band-pass filter with only two general-purpose amplifiers. One key issue is that high DC gain is needed on the pressure waveform through the INA. The filter rejects DC and band passes the 0.5-Hz to 7-Hz frequencies with a total of 70 dB or more to pick up the μV-level oscillations.

Several topologies were simulated using the Filter Design Tool by TI to balance filter performance and noise. The first design, shown in Figure 2-6, was a 2nd order Sallen-Key low-pass stage followed by a 2nd order Sallen-Key high-pass stage, both with Butterworth response. This resulted in a relatively flat frequency response, but unfortunately did not add enough gain without significant noise increase.

For the second design, a 2nd order HP stage followed by a 2nd order BP stage was able to effectively add three zeroes at the low frequency stop band to filter the 30 dB of DC gain much better with only two amplifiers. This yielded the best filter performance for the application. However, total noise was simulated at about 540 μV_{PP}.

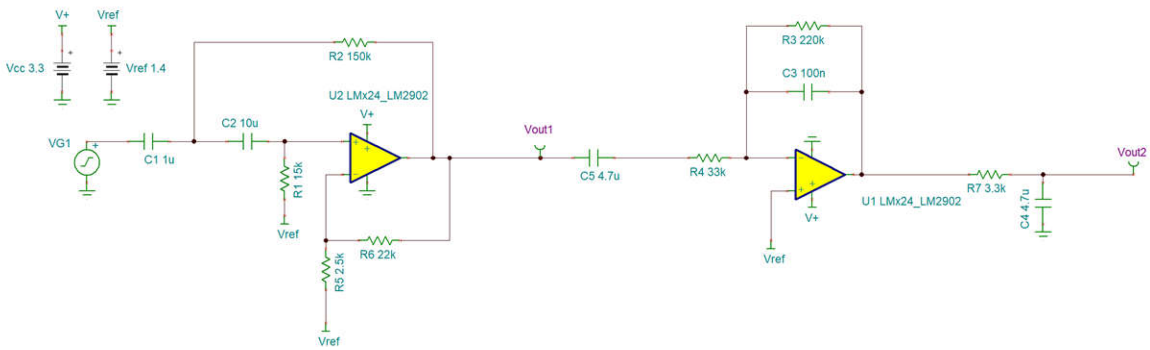


Figure 2-6. Sallen-Key High-Pass + Band Pass

Figure 2-7 shows the third circuit design, a simple 2-stage BP. This filter yielded the best noise performance and also the lowest passive count. One drawback is that the response is not flat when trying to keep a narrow pass band.

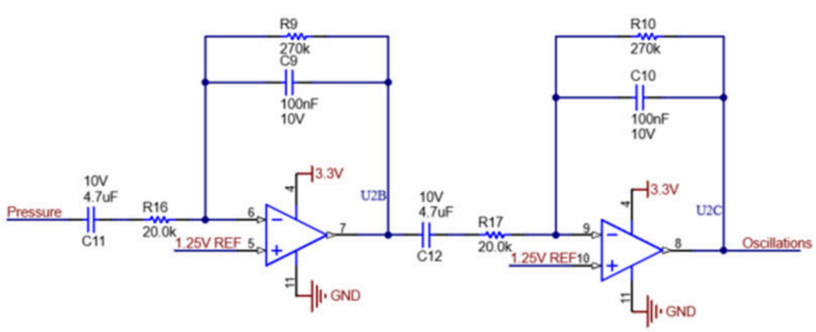


Figure 2-7. Two-Stage Band-Pass Circuit

The two-stage band pass was designed to prioritize, low-noise, stop-band attenuation, and component cost. In the best setup, an NP0/C0G, or at least X5R is preferred for improved tolerance over temperature and lower noise.

$$f_{Low} = \frac{1}{2\pi \times 20\ k\Omega \times 4.7\ \mu F} = 1.7\ Hz \quad (3)$$

$$f_{High} = \frac{1}{2\pi \times 270\ k\Omega \times 100\ nF} = 5.9\ Hz \quad (4)$$

2.3 Highlighted Products

2.3.1 MCU-MSPM0L1306

This device is selected as the system MCU and is the brain of the system. The device can perform the following actions:

- Measure systolic, diastolic, and heart rate in measure mode
- Send data and results serially for visualization

This MCU has a 32-MHz Arm® Cortex®-M0+ core, 64k flash, and 4k SRAM. The MCU is differentiated because of high-performance analog peripherals. The device includes one 12-bit 1.68-Msps SAR ADC with up to 11.1 typical ENOB and 71 dB SNR, as well as additional 128x hardware oversampling. This MCU includes two zero-drift, zero-crossover chopper operational amplifiers (OPA) with down to 0.5-μV/°C drift and 2-μV_{PP} 1/f noise with chopping mode.

These devices also offer intelligent digital peripherals such as four 16-bit general purpose timers, one-windowed watchdog timer, and a variety of communication peripherals including two UARTs, one SPI, and two I2C interfaces.

The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The run mode has a power consumption of 71 μA/MHz, 1 μA standby with SRAM and register fully retained, and shutdown mode with down to 61-nA current consumption with IO wakeup capabilities.

Figure 2-8 shows more of the MSPM0L1306 blocks.

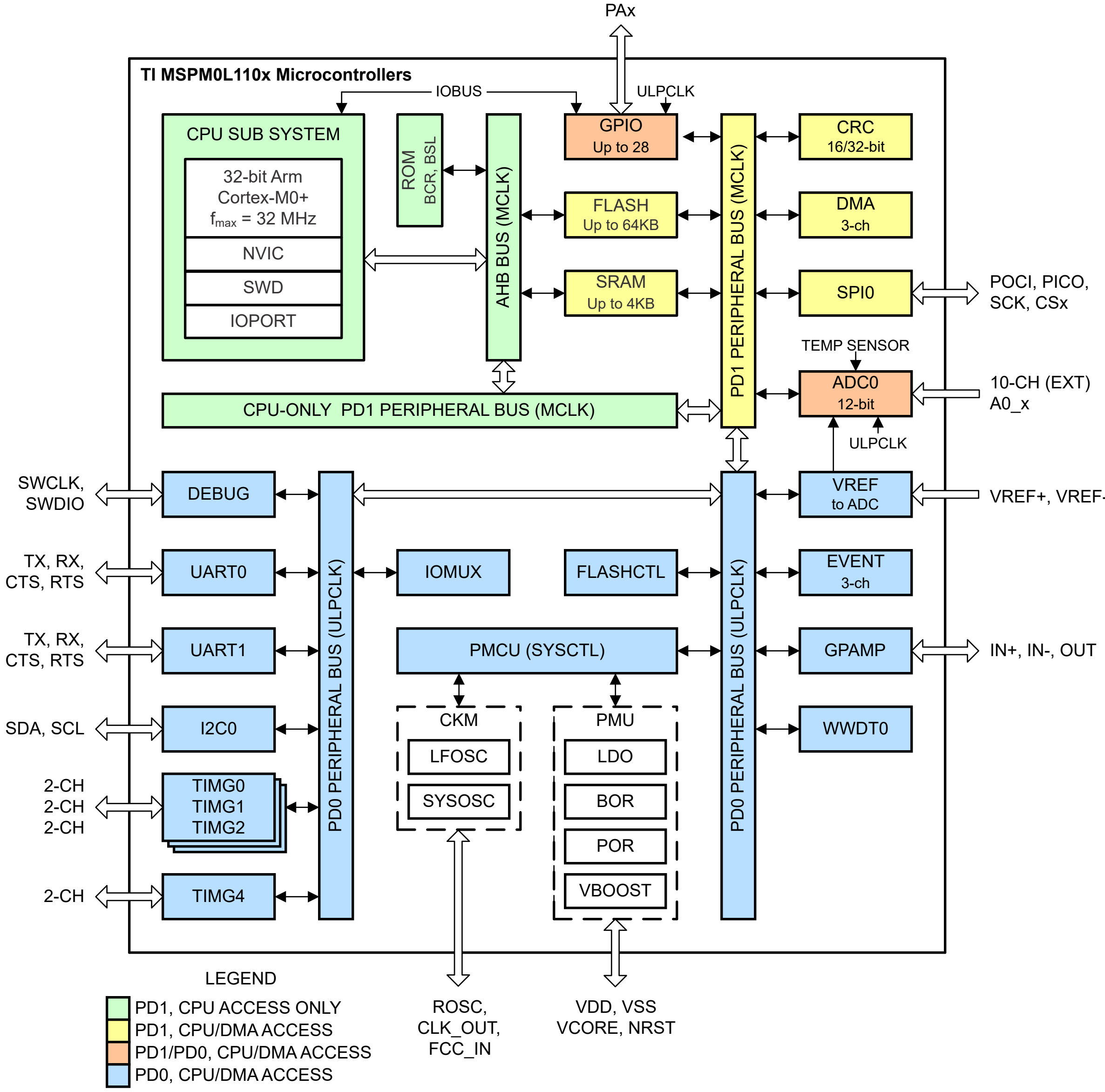


Figure 2-8. MSPM0L1306 Functional Block Diagram

2.3.2 OPA-LMV324A

The LMV324A is a quad low-voltage (2.5 V to 5.5 V) operational amplifier with rail-to-rail output swing, 5.1-μV$_{PP}$ 1/f noise, ±1 mV input offset, 10-pA input bias current, and quiescent currents of 70 μA/Ch. The LMV324A is the most cost-effective design for applications where low-voltage operation, space saving, and low cost are required. Additional features of the LMV324V are a common-mode input voltage range that includes ground, 1-MHz unity-gain bandwidth, and 1.7-V/μs slew rate. Figure 2-9 shows the functional block diagram.

One of the amplifiers is used to bias the pressure sensor with a constant current. A second amplifier is used to create a bias reference voltage used for the INA and band-pass filters. The remaining amplifiers are used for a two-stage band-pass filter.

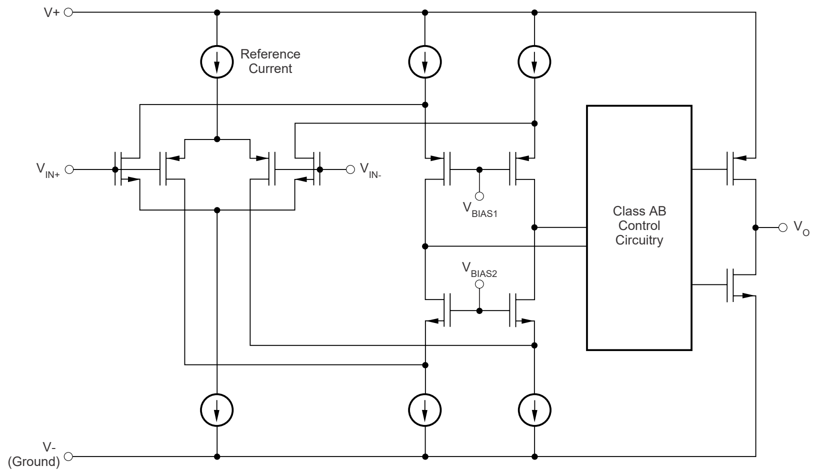


Figure 2-9. LMV324A Functional Block Diagram

2.3.3 LDO-TPS7A2433

The TPS7A24 is an 18-V, low quiescent current (2 µA at no load), low-dropout (LDO) linear regulator that comes in both fixed and adjustable variants. The low I_Q performance makes the TPS7A24 an excellent choice for battery-powered or line-power applications that are expected to meet increasingly stringent standby-power standards. This device comes in fixed-output and adjustable versions and 1.25% accuracy over temperature.

Additionally, the TPS7A24 also incorporates overcurrent, overshoot pulldown, and thermal shutdown protection. Figure 2-10 shows the functional block diagram.

This device converts the input voltage from the battery (approximately 6 V) to 3.3 V and supplies the voltage to the MCU. The device can provide stable input voltage to the MCU. While a buck converter can be added to provide higher efficiency when stepping down the 6-V battery output, the LDO does not power the motor or valve which are the main sources of current draw. Limiting the efficiency losses to mainly the sleep state current draw of the MCU and amplifiers.

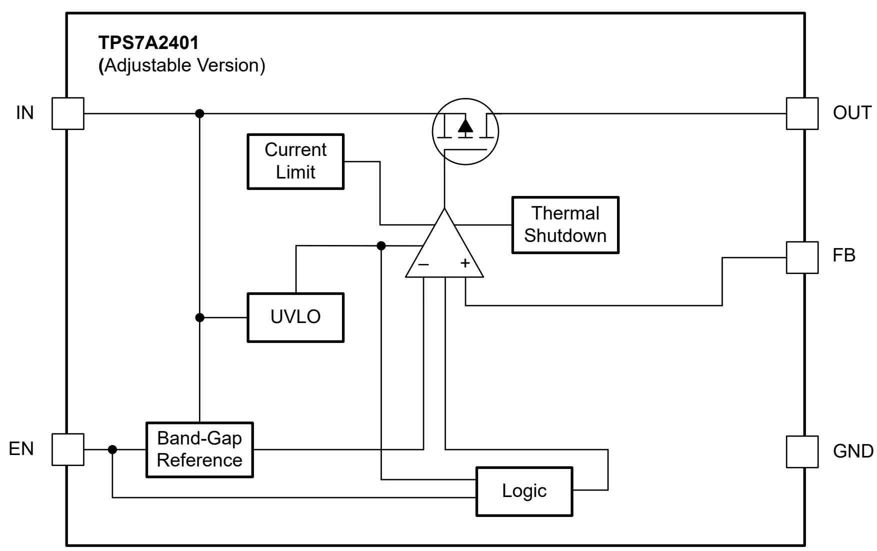


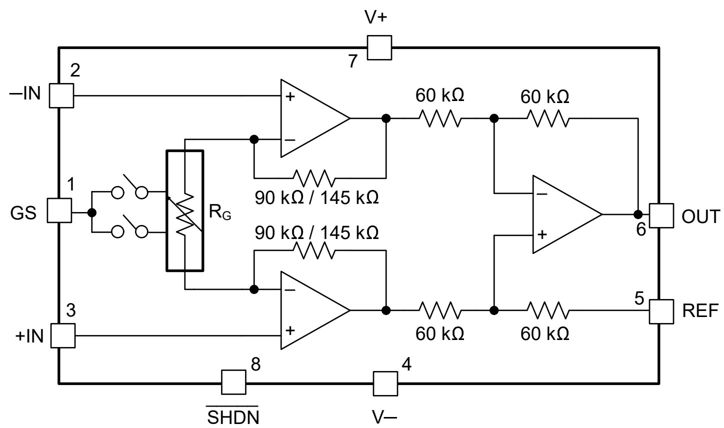
Figure 2-10. TPS7A2433 Functional Block Diagram

2.3.4 INA350

This device is a low-cost instrumentation amplifier optimized for size and low power. The INA350 can be selected as the pressure sensor INA through jumper configurations. This conditions the pressure sensor output for outstanding use of the dynamic range of the ADC. This device has a 3.2-µV_{PP} 1/f noise, a ±0.2-mV input offset, and ±0.6-µV/°C voltage offset over temperature. The device has many desirable features for battery-operated BPMs such as automatic shutdown when idle, package options down to 1.5 mm × 2.00 mm, and integration of passives for a smaller design versus discrete implementations. Figure 2-11 shows the functional block diagram.

The INA350 comes in two different gain variant versions. The INA350ABS can be used in gains of 10 or 20 V/V while the INA350CDS used in this design can be used in gains of 30 or 50 V/V.

Although not used in this design, the new INA351 and INA351A can also be used for this design. The INA351 adds an integrated voltage reference buffer, and the INA351A allows the voltage reference pin to be taken to an external pin so the device can be used for offset correction or to bias additional circuits.



Note: 90 kΩ for INA350ABS and 145 kΩ for INA350CDS

Figure 2-11. INA350 Functional Block Diagram

2.3.5 DRV8210

This device is a brushed motor driver that use GPIO or PWM inputs from the MCU to drive both the pump and valve used to inflate and deflate the cuff. Two independent half-bridges capable of 1.76 A per channel are integrated in a design that is smaller against discrete alternatives. The DRV8210 comes as small as 1.2 mm × 1.60 mm and includes an auto-sleep feature with lower than 84.5-nA current draw at 5 V. Figure 2-12 shows the functional block diagram.

This device only requires two bypass capacitors and integrates undervoltage lockout (UVLO), overcurrent protection (OCP), and device overtemperature.

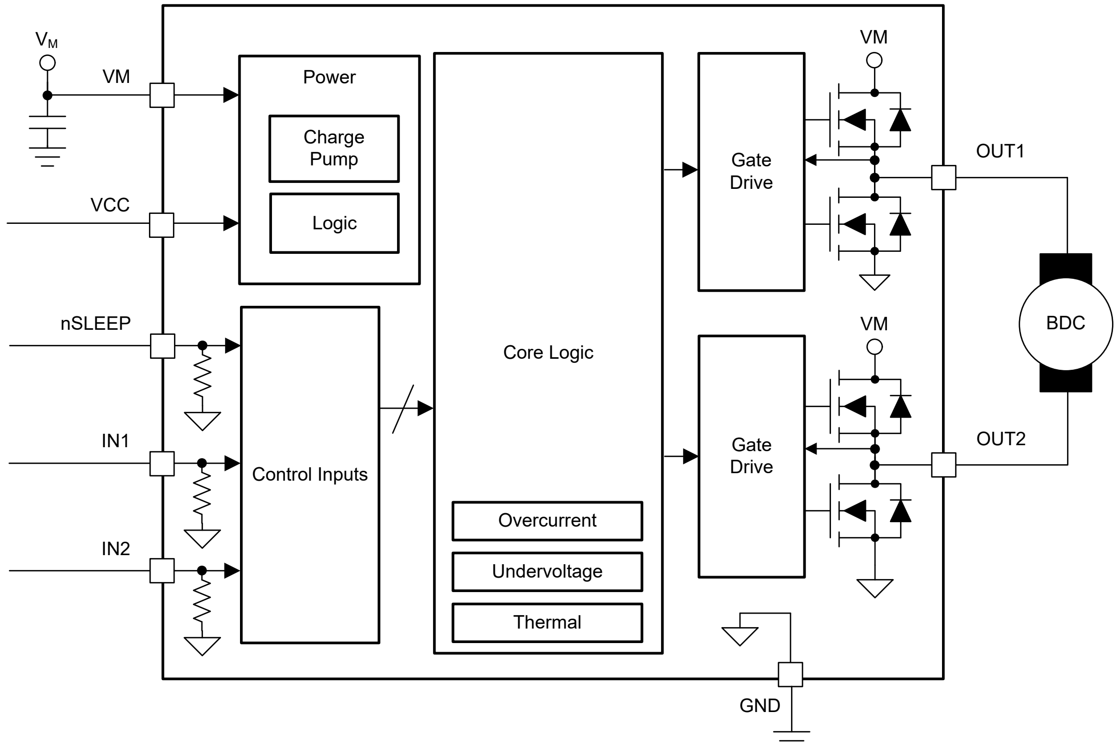


Figure 2-12. DRV8210 Functional Block Diagram

2.3.6 ATL431LI

The ATL431LI device provides a 2.5-V reference to the ADC as well as 1.25-V rail generation circuit used to bias the INA and band-pass filter. This device is a shunt reference selected for the 0.5% accuracy and maximum temperature drift of 17 mV at a very low cost.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Hardware Requirements

To set up the hardware, connect all the parts of the system. Before connecting, assemble the components to the board, see Section 3.1.1.

3.1.1 System Connection

Connect the gas path as shown in Figure 3-1. The pressure sensor, pump, valve, and cuff must be connected without any leaks.

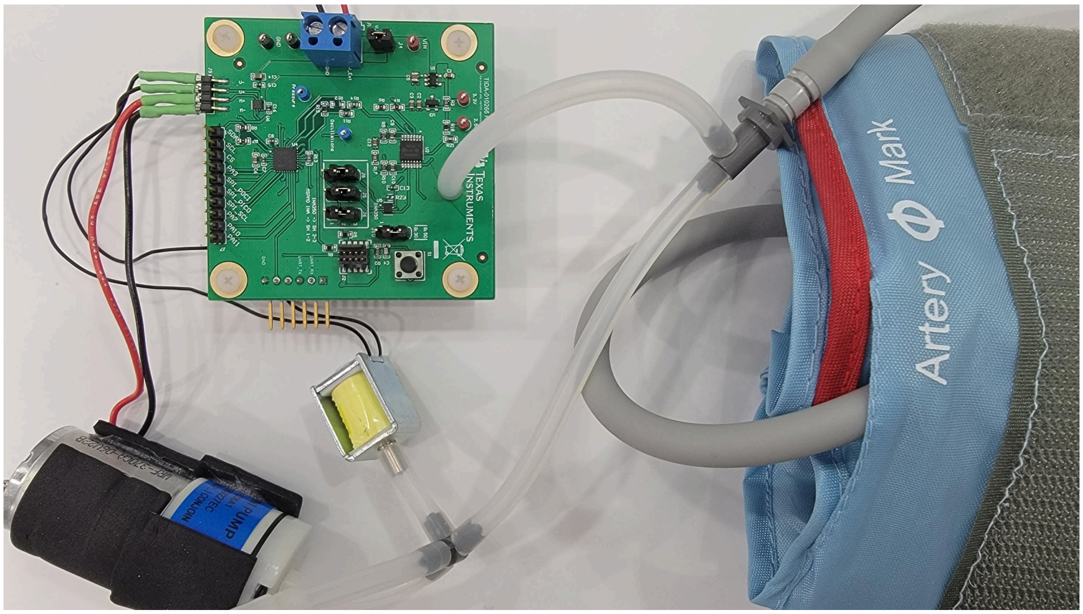


Figure 3-1. Connection of Cuff, Pump, Valve, and Sensor for Gas Path

A summarized process for making the electronic connections follows:

1. Connect one wire of the pump to M+ and the other to M–.
2. Connect one wire of the valve to V+ and the other wire to V– (see Figure 3-2)
3. Connect a 4-AA battery holder to the terminal J1.
4. Connect a UART to USB cable on terminal J3 .
5. Optional - For code changes using CCS, use an XDS110 on terminal J2.

To see or collect raw data, connect UART to the PC.

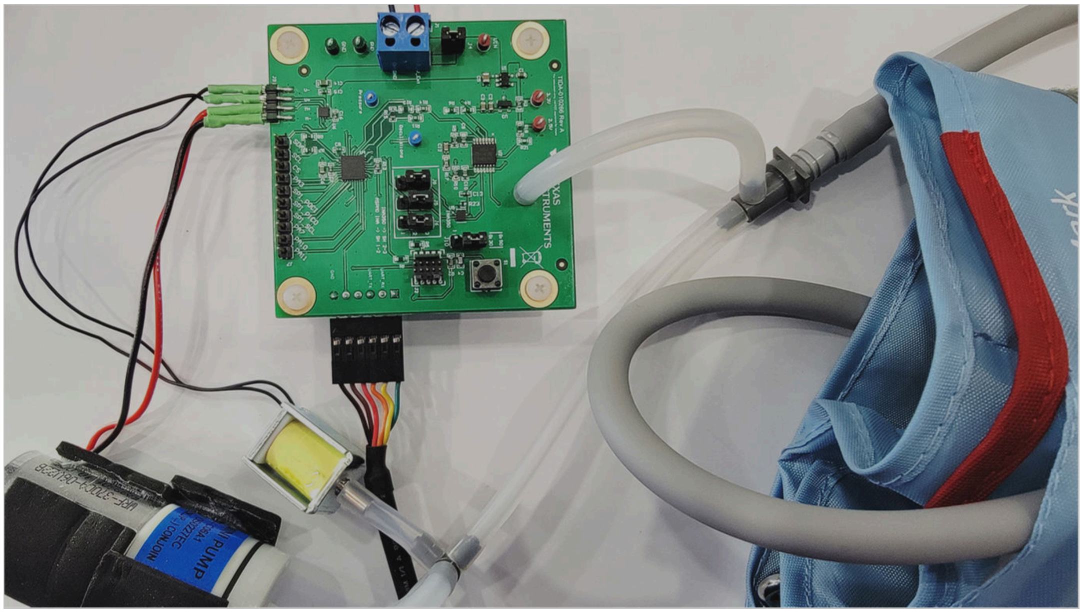


Figure 3-2. Connect to the Board

3.2 Software Requirements

To start using the demonstration, complete the following steps:

1. Download CCSTUDIO.
2. Download the latest MSPM0-SDK.
3. Import the software development kit into CCSTUDIO.

Figure 3-3 summarizes the general flow of the software.

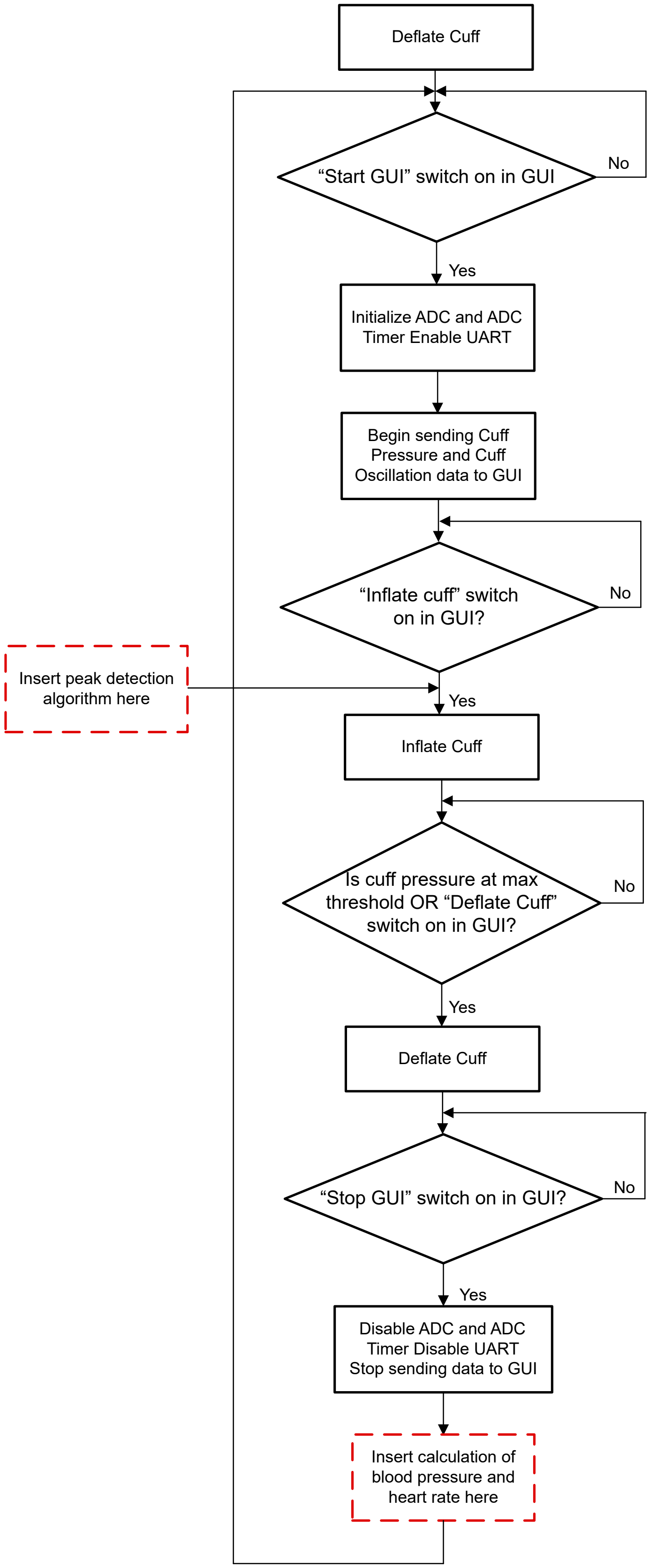


Figure 3-3. Software Flow Chart

3.3 Running the Demonstration

To run the demonstration, complete the following steps:

1. Open CCSTUDIO
2. Import the "blood_pressure_monitor demo" project inside the SDK *demos* folder as seen in Figure 3-4
3. Build the project and program the board
4. Click on the GUI link inside the README file to setup the demonstration GUI to reach Figure 3-5

Note

Examine the README file to understand the peripherals and pins used for this design.

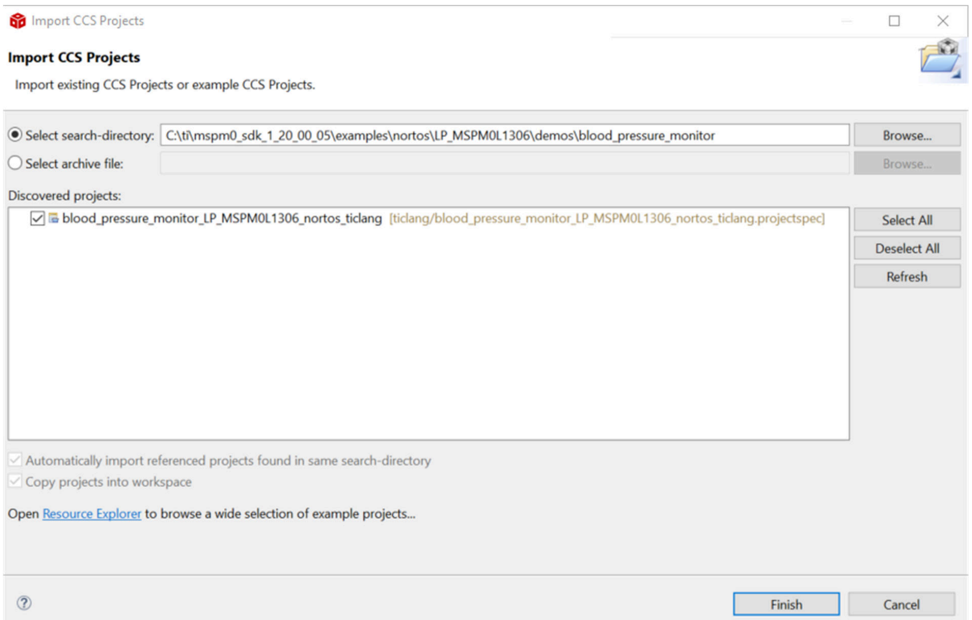


Figure 3-4. Importing CCS Project

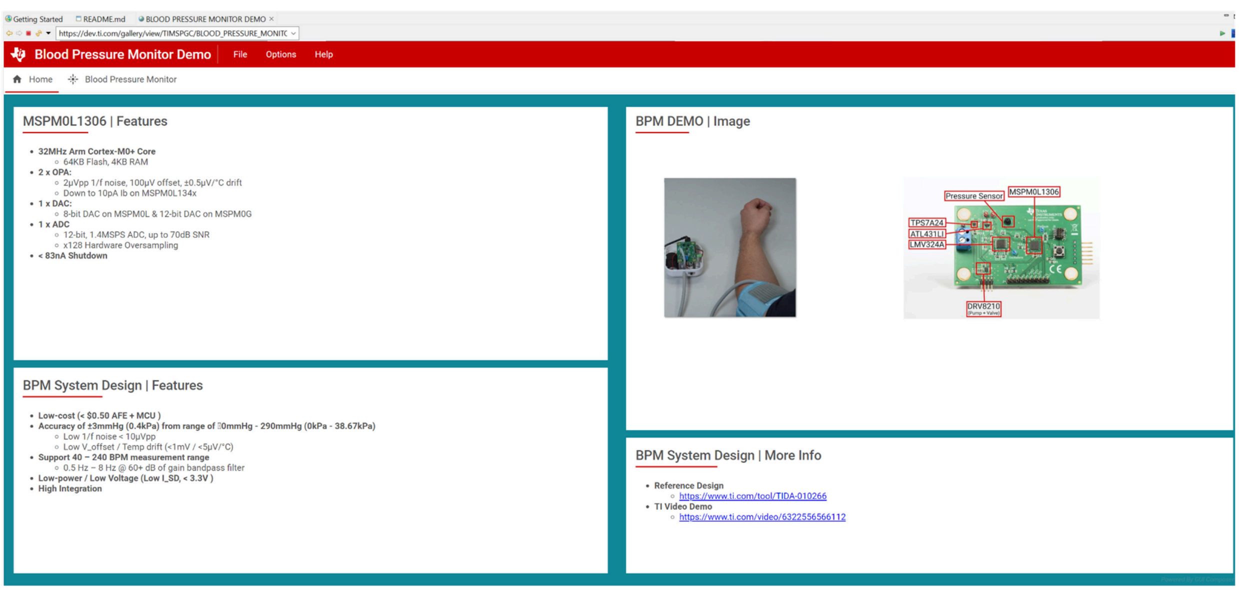


Figure 3-5. BPM GUI Home Tab

The following list provides a summary of the instructions to operate the GUI and generate the images shown in Figure 3-6.

1. Go to the *Blood Pressure Monitor* tab.
2. Click on the *Start GUI* button.
3. The board starts streaming both ADC channels over UART and the channels are displayed on the GUI windows.
4. Click the *Inflate Cuff* button to inflate the cuff to a target threshold pressure.
    a. At this point the program stops the pump at the target pressure and starts to open the valve to deflate the cuff and allow for cleaner sensor measurements.
5. To stop the demonstration, click on *Deflate cuff* to open the valve and turn off the pump, and then click *Stop GUI*.

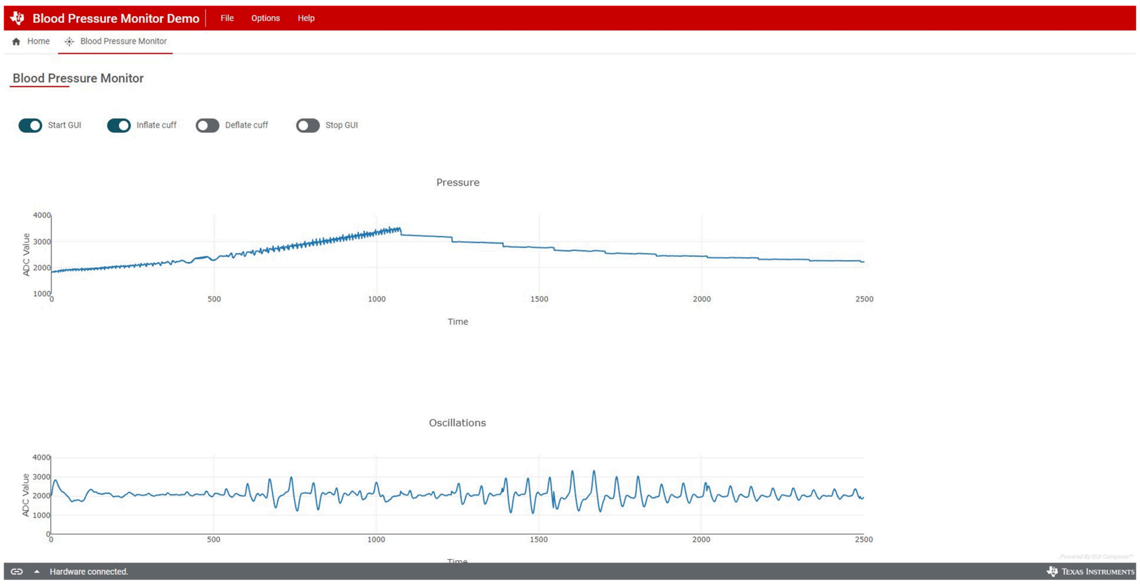


Figure 3-6. BPM GUI Waveforms

3.4 Test Results

The user must not move during measurement and the cuff must be put on correctly. The GUI capture detects oscillations both on the inflation and deflation phases of the measurement. The difference is the level of noise while the pump is on versus when the pump is off, which improves the SNR and thus overall accuracy. However, with the purpose of speeding up the measurement, the oscillations can be captured on the inflation phase only.

After implementing the blood pressure algorithms, the demonstration can be used to quickly evaluate the performance.

4 Design and Documentation Support

4.1 Design Files

4.1.1 Schematic

To download the schematics, see the design files at TIDA-010266.

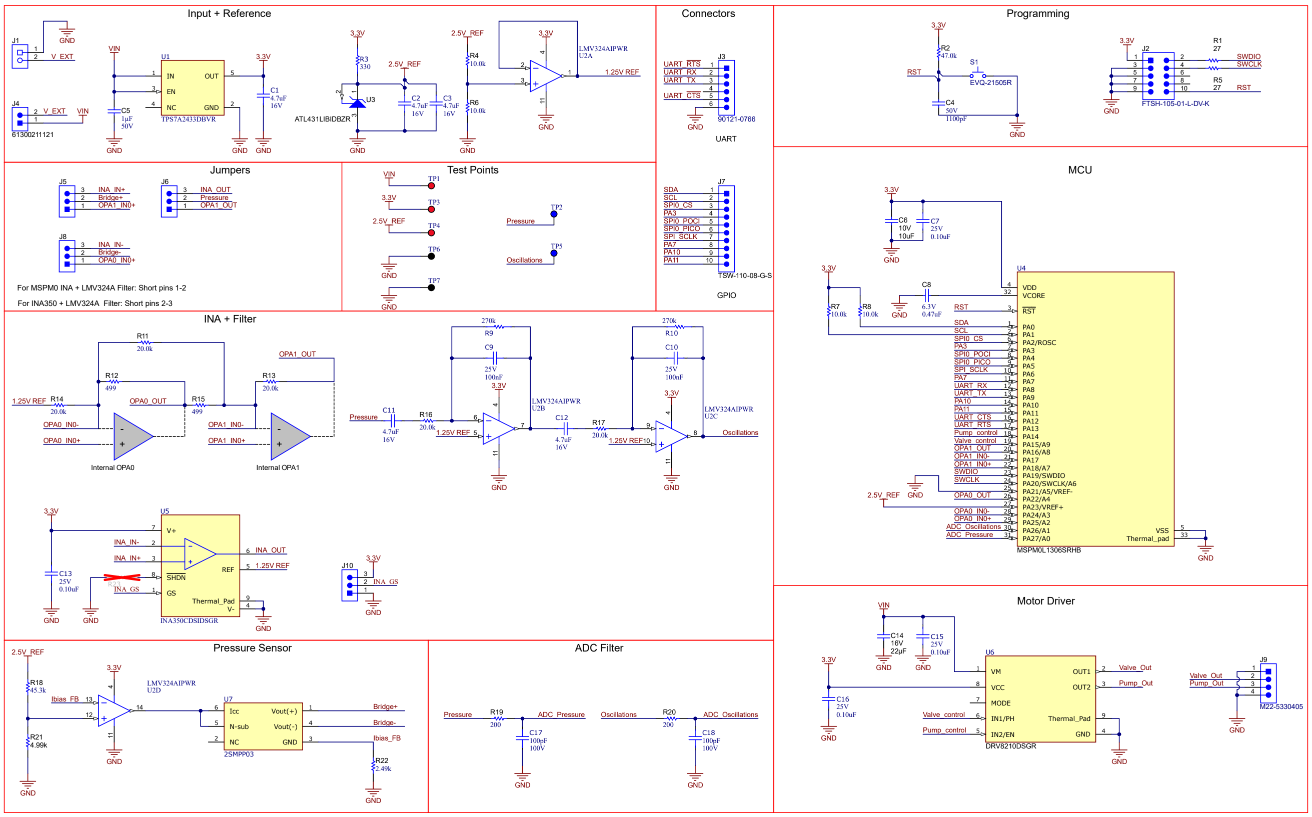


Figure 4-1. Schematics

4.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010266.

4.1.3 PCB Layout Recommendations

This reference design was done as a 4-layer design to fit both signal-chain selectable options. However, in a real implementation with only one of the signal-chain options, a 2-layer design suffices.

4.2 Tools and Software

Tools

Code Composer Studio™	Code Composer Studio is an integrated development environment (IDE) for TI's microcontrollers and processors. Code Composer Studio comprises a suite of tools used to develop and debug embedded applications. Code Composer Studio is available for download across Microsoft® Windows®, Linux®, and macOS® desktops. This product can also be used in the cloud by visiting the TI Developer Zone.

4.3 Documentation Support

1. Gallardo JE, Cotta C, Ferandez AJ. *On the hybridization of memetic algorithms with branch-and-bound techniques.* IEEE Transactions on Systems, Man, and Cybernetics, Part B:Cybernetics, 2007, 37(1): 77-83.
2. Texas Instruments, *MSP430x5xx and MSP430x6xx Family* user's guide
3. Texas Instruments, *MSPM0L130x Mixed-Signal Microcontrollers* data sheet

4.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

Linked content is provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

4.5 Trademarks

5 About the Author

JOHN VARELA MUNOZ is a Systems Engineer at Texas Instruments, where he is responsible for developing system-level designs for the medical sector. John earned his bachelors and masters degrees in electrical engineering from the University of Florida and Texas A&M University, respectively.

AMRUTA DEOLE is an applications engineer at Texas Instruments, where she is responsible for supporting customers within the MSP product line.

IMPORTANT NOTICE AND DISCLAIMER