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Ultrasonic Water Flow Measurement Using Time to Digital Conversion

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Design Resources

TIDM-ULTRASONIC-FLOW-TDC	Design Page
MSP430FR6989	Product Folder
TDC1000	Product Folder
TDC7200	Product Folder
TPS62740	Product Folder
TPS61291	Product Folder
TPD8E003	Product Folder

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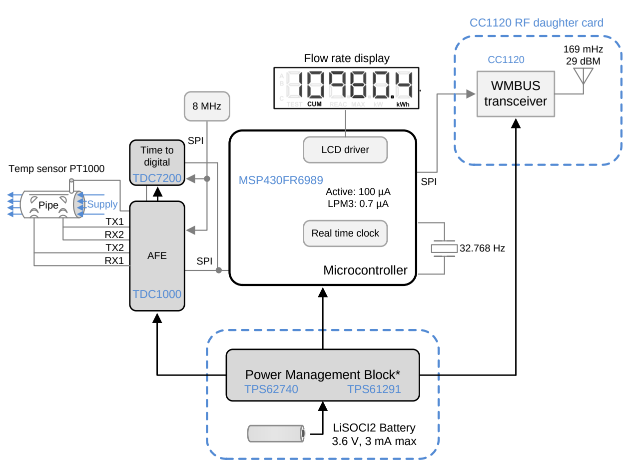
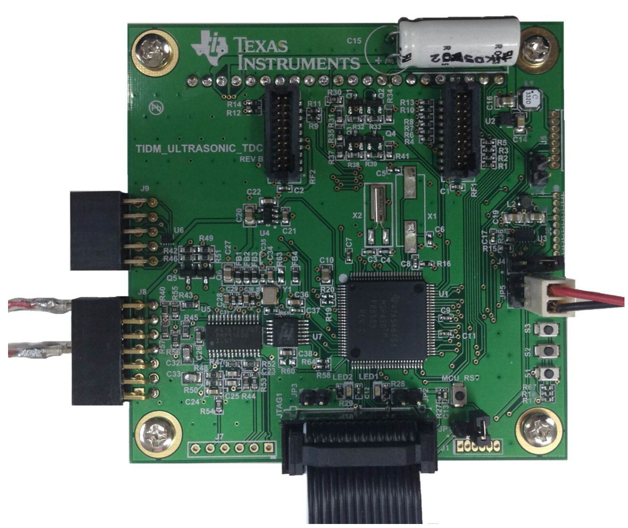
Design Features

- Ultra-Low-Power Design
- Ultrasonic Time of Flight Measure
- Small Form Factor
- High Efficiency DC-DC Converter for System Power
- Super-Cap Design for Power Supply of RF Module
- Platform Design With Sockets for RF, Power Module, and MCU I/O
- PC GUI

Featured Applications

- Water Meter
- Gas Meter
- Heat Meter





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1 System Description

This ultrasonic flow meter (water, gas, or heat meter) reference design with LCD is built using the TDC1000, TDC7200, and MSP430FR6989 [(1)] . The TDC chip sets measure the time of flight of ultrasonic signals traveling in the media with an accuracy of 52 ps as the LSB of the TDC7200.

The TDC1000 is the analog front end, which transmits and receives signal. The received signal is amplified and passed to a comparator with a tunable internal reference voltage to output a sequence of pulses called stop pulses. The TDC7200 is a high-resolution timer to measure the time of flight of signal, starting from the time at which it is transmitted from the TDC1000 to the time the stop pulses are output.

This TI design is battery powered with an ultra-low-power design. It mainly consists of the MCU, the measurement chip set. A socket connecting the power supply circuit is provided for the RF module, which is connected to the MCU through SPI and I/O.

Ultrasonic transducers can be directly connected to the headers J8 (see the schematic diagram) of the board. The user can also build an external board with connectors plugged into the headers of J8 and J9.

Two DC-DC convertors are provided. The TPS62740 is used for power supply for the MCU and measurement system while the TPS61291 is used for the RF module. Both circuits are connected with connectors J5 and J6.

Three push buttons are provided for users to implement more functions. This TI design is a platform based design. Users can connect their own external boards to the sockets or connectors to form a highly sophisticated design.

(1) The MSP430FR6989 is used to get to the market quickly. The ESI module in this MCU is not used in this design. Evaluate the MSP430FR697x, a variant without an ESI module.

2 Design Features

2.1 Ultra-Low-Power Design

The whole system consumes average current of 10.5 µA with a sampling rate of one measure per one second. The LCD and RF module are in an off state to reduce power consumption. This is the first version with a low-power design.

During the low-power mode, the system voltage is set to 2.5 V and consumes 0.5 µA. The only active components during this state are the DC-DC converter TPS62740, the 32.768-KHz crystal, and the timer of the MCU. The default setting of timer is one second. Once the timer reaches the count, the system wakes up and the system voltage generated by the TPS62740 is set to 3.3 V by the MCU.

During the active mode, power is switched on for the TDC1000 and TDC7200, which are then initialized and reset by the MCU through SPI. These chip sets will perform the measurement.

Once the measurement completed, the power supply to the TDC1000 and TDC7200 is switched off, and the MCU enters low power mode 3 with the system voltage set to 2.5 V to lower the current consumption.

When switching the power of the devices on board to an active or low power mode state, a specific sequence and settling time is required to minimize the leakage current and the time for stabilization. For details, see the short functions TDC_Chips_On() and TDC_Chips_Off() in Main.c.

2.2 Ultrasonic Measurement for Time of Flight

The basic connection of the measurement analog front end to the MCU is shown in the block diagram of Figure 1. The TDC1000 has connections to two ultrasonic transducers. The MCU is connected to TDC chips with SPI and other control lines. During the measurement period, the MCU will power up TDC chips and initialize them through SPI. The time of flight measurement process is done in the TDC1000 and TDC7200 without intervention of MCU. After completing the process, the measurement data is stored in the TDC7200. The MCU will then fetch the data by SPI and switch off the TDC chip set to save power. The rest of the calculation is done in the MCU and the LCD will display the result. In this reference design, however, the MCU sends the data to the PC GUI, which will process the calculation. The MCU enters into low power mode and will repeat the whole process after a time interval of one second (default setting).

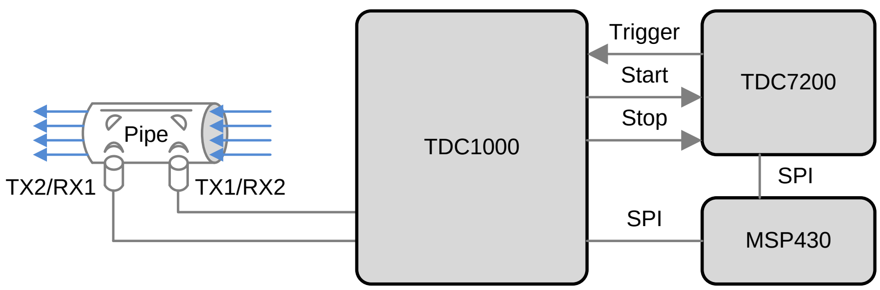


Figure 1. Measurement Front End

Figure 2 shows the overview working principle of the TDC1000. The time of flight is to measure the time taken from the transmitting transducer to the receiving transducer. In the measurement process, the MCU sends a start message through the SPI to the TDC7200, which then sends a trigger signal to the TDC1000. At the same time, the TDC1000 will send a start pulse to the TDC7200 and transmit the first ultrasonic signal through TX1 and received by RX1. This is in the same direction as the flowing media, called upstream.

In the arrival of the received signal, the TDC1000 amplifies the signal and passes it to a comparator to generate stop pulses, which are then measured by the TDC7200 to get the time of flight of the signal. Registers of the TDC7200 containing the measurement data are then sent to the MCU through SPI for further processing.

To measure differential time of flight, the TDC1000 needs to repeat the same process with opposite direction, in downstream of the flowing media, transmitting signal from TX2 and received by RX2. The differential result is obtained by time taken for downstream minus that for upstream.

The transmitting pulses to a transducer are a square wave. Its frequency can be pre-defined by internal registers of the TDC1000.

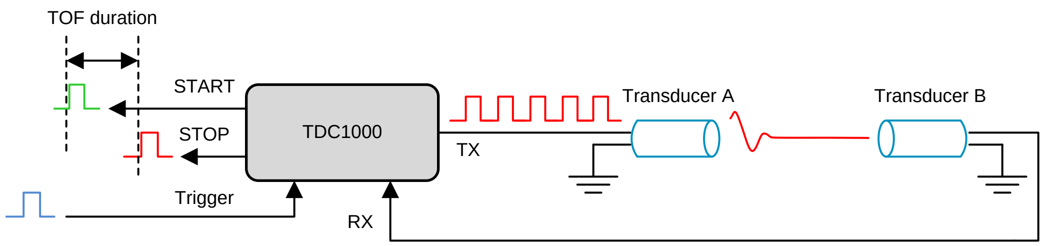


Figure 2. Time of Flight Measurement

Figure 3 shows an amplified received signal of the TDC1000 with a DC bias of VCOM. The signal is passed through a comparator with an internal reference voltage as the threshold. When the voltage of the signal is lower than the threshold, a stop pulse is then generated when the signal crosses the VCOM. The number of stop pulse can be set with the registers. However, the maximum number of stop pulses processed in the TDC7200 is five. Therefore, when setting the number of pulses in the TDC1000, it has to be equal to or larger than the number of pulses set in the TDC7200.

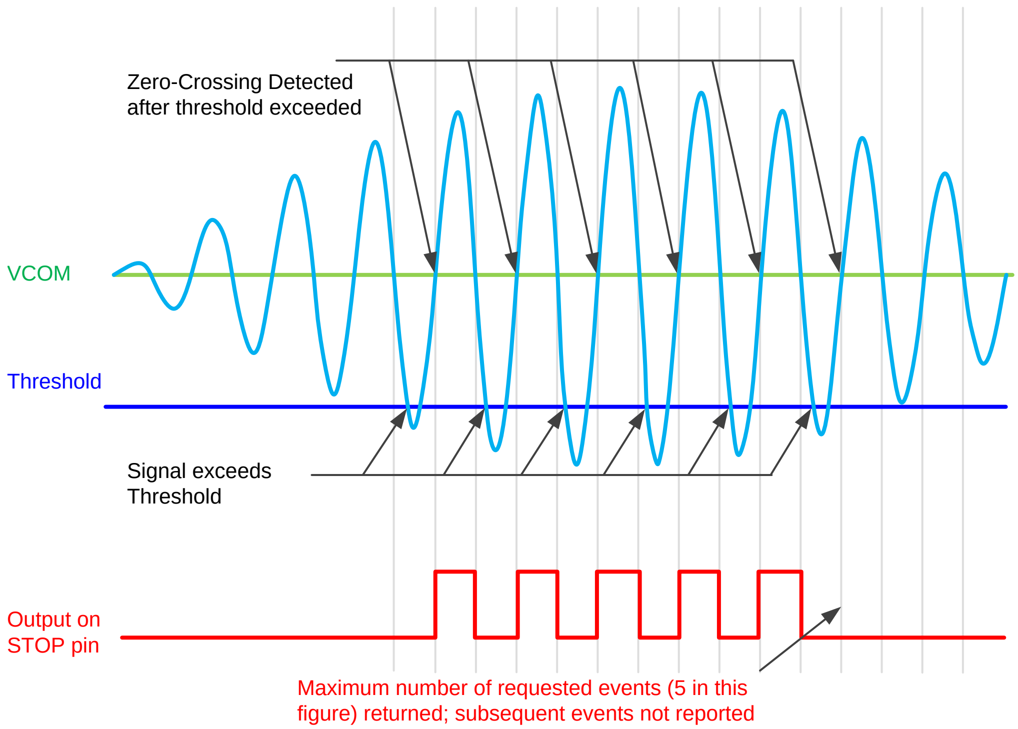


Figure 3. Received Signal to Stop Pulses Conversion

Figure 4 shows how the TDC7200 makes the measurement. There are 13 registers, each of which has 24 bits to record the timing information. When the start pulse is generated from the TDC1000, the TDC7200 starts to measure with the external clock of 8 MHz (in this TI design). The register "Time 1" is to measure the time taken from the edge (polarity selectable) of the START pulse to the rising edge of the 8-MHz clock. This measurement is done using the internal high resolution timer of the TDC7200 with the fine resolution of 52 ps (LSB) in average.

When the ultrasonic signal starts flying through the media in a flow meter, a timer register "CLOCK count 1" is counting the number of clock cycle of 8 MHz until the first STOP pulse is received. Register "Time 2" is to measure the time taken from the edge of the first STOP pulse to the edge of the 8-MHz clock (the same way as "Time 1"). With the information from "Time1", "CLOCK count 1", and "Time 2", the time of flight from the edge of START pulse to the edge of the first STOP pulse can be calculated.

The timer is kept running, and the received signal propagates to generate the second STOP pulse. Similarly, the same process is repeated for the second STOP pulse to obtain "CLOCK count 2" and "Time 3". The process is kept on until the fifth STOP pulse is measured.

Because there might have some deviation of high resolution timer of the TDC7200 in every measurement, the device needs calibration every time. Registers "Calibration 1" and "Calibration 2" ("Cal 1" and "Cal 2" in Figure 4, respectively) are used. In the project's default setting, Cal 1 records timing information from the high resolution timer in the period of 1 clock cycle of 8 MHz while Cal 2 does the same for 10 clock cycles of 8 MHz.

Equation 1 calculates the calibration of the high resolution timer as follows:

$$\text{Cal } 1 \times \text{normLSB} + \text{offset} = 0.125\ \mu\text{s}$$

$$\text{Cal } 2 \times \text{normLSB} + \text{offset} = 10 \times 0.125\ \mu\text{s}$$

$$\text{normLSB} = \frac{(10 - 1) \times 0.125\ \mu\text{s}}{\text{Cal } 2 - \text{Cal } 1}$$

where

- normLSB = normalized least significant bit
- 0.125 µs = time for 1 clock cycle of 8 MHz (1)

Similar to calculating for other STOP pulses, Equation 2 calculates the time of flight for the first STOP pulse as follows:

$$\text{Time of flight} = (\text{Time } 1 - \text{Time } 2) \times \text{normLSB} + \text{CLOCK count } 1 \times 0.125\ \mu\text{s} \tag{2}$$

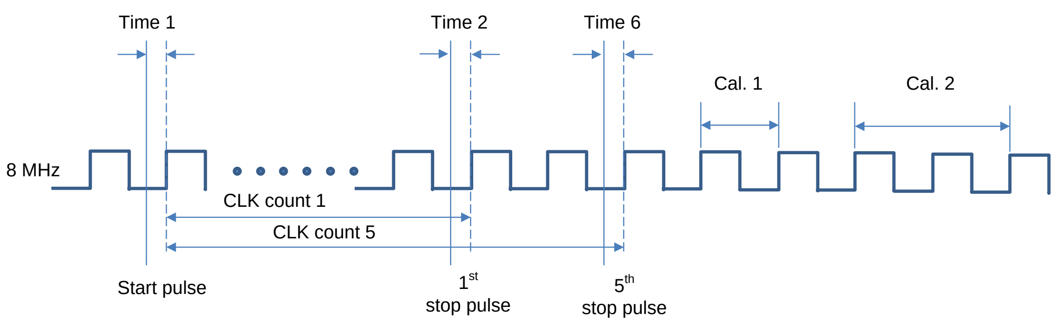


Figure 4. Timing Registers on Five Stop Pulses

2.3 Small Form Factor

The PCB board size is 3×3 inches, which can fit into most of the meter casing. Half of the board is occupied with a big LCD and a socket for the RF module. The user can further reduce the board size with a smaller LCD module. The PCB area for the main chip set of the TDC1000, TDC7200, and MCU is merely 1.1 × 2.3 inches.

2.4 High Efficiency DC-DC Converter for System Power Supply

The TPS62740 step-down converter is used to convert 3.6 V of lithium battery into 3.3 V as system voltage in active mode with an efficiency up to 90%. It takes a typical quiescent current of 360 nA. The output voltage is selectable. When the system is in standby mode after each measurement, the output voltage is set to 2.5 V to reduce overall current consumption to 0.5 µA.

2.5 Super-Cap Design for Power Supply of RF Module

When an RF module is transmitting signal, a large current will be consumed. However, some lithium batteries have a limitation of output current. To cope with this situation, a super capacitor is used as a buffer to store the charges from the battery and to supply large current for the use of RF power amplifier.

In the daily operation of a flow meter, the RF module is only switched on for a short time to send out the reading of the meter to the data concentrator, a few times per day or per week. In the standby mode, the module is switched off to save power. During the standby mode, the super capacitor is charged up to 2.5 V. In transmitting mode, a boost converter (TPS61291) connecting to the super cap is enabled to step up the output voltage to 3.3 V, which will supply the power to RF module. All the current used in the RF module will then only be taken from the supper capacitor.

2.6 Platform Design

The board is designed with a platform-based concept. It has the core function of measurement unit and an MCU with an LCD module. The board also has reserved some sockets for adding on extra functionalities or circuit modification.

One important socket is the RF socket, which is connected to the SPI and I/O port of the MCU and has a dedicated power supply module. This socket can plug in with the communication module, like Wi-Fi, Bluetooth, or M-bus of a wired or wireless type. It also can be used as an extended connection to other device modules.

The power supply module can be modified with the sockets connecting to it. The user can remove the power components and replace it with a new module connecting to the sockets.

While programming the MCU, the user can select the JTAG interface or the Spy-Bi-Wire connection. In the socket of the Spy-Bi-Wire, it uses a six-pin socket with a UART pin directly connected to MCU. This socket is compatible with the eZ-FET tool of the MSP430.

2.7 PC GUI

A PC GUI is provided to control the operation of the system. This GUI has the panel for the TDC1000 and TDC7200 set up. It can monitor the time of flight for each STOP pulse. The GUI has reserved some other functions like the flow rate and temperature sensing. However, the first version of the MCU firmware has not been implemented with these functions yet.

3 Block Diagram

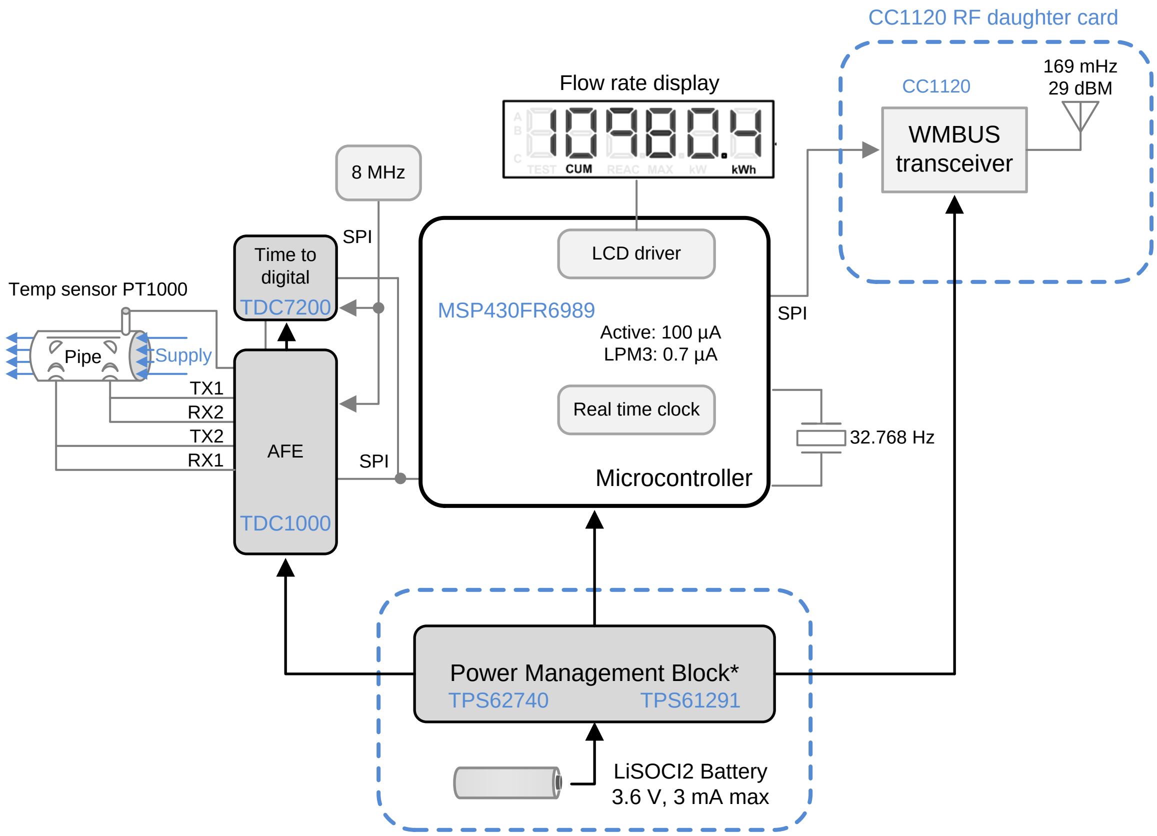


Figure 5. System Block Diagram

4 Circuit Design

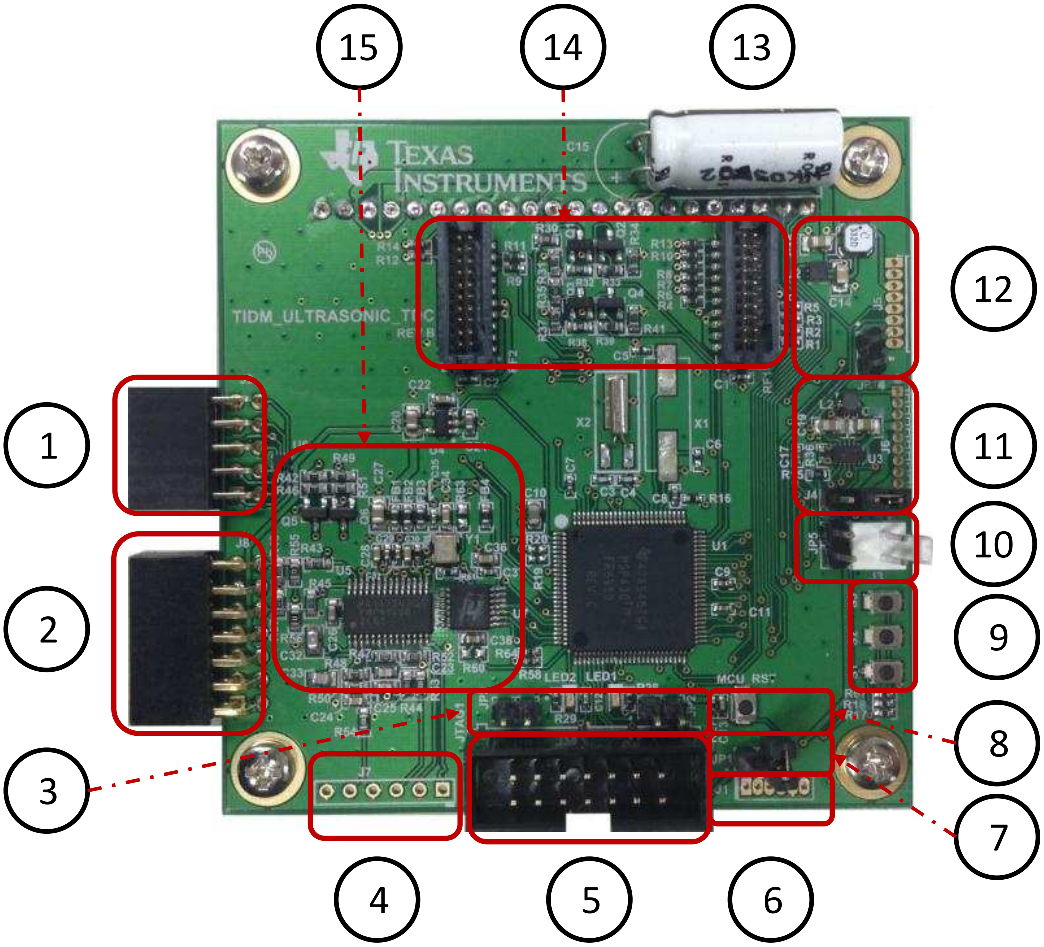


Figure 6. TI Design of Ultrasonic Flow Meter

This solution of the ultrasonic flow meter is built on the TDC1000, TDC7200, and the MCU MSP430FR6989 with an LCD display soldered on the bottom size of the board. This board is powered by a 3.6-V lithium battery, which is down converted to 3.3 V through a voltage selectable buck converter of the TPS62740. For the operation of this board, it can be descripted with 15 parts controlled with the MCU. Details follow for each part:

1. An external board can be built and plugged into this socket and the socket of Part 2 to enhance its features.

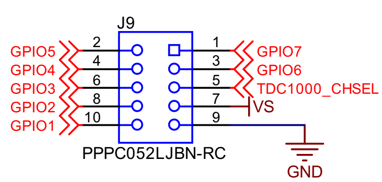


Figure 7. Socket (J9) Connecting to I/O of MCU

2. Ultrasonic transducers are to be connected through this socket.

   J8 also provides two pin sockets for external temperature sensors connecting RTD1 and RTD2 signals in the circuit. These signals are used when temperature of the media in a meter is included for the measurement, like heat meters.

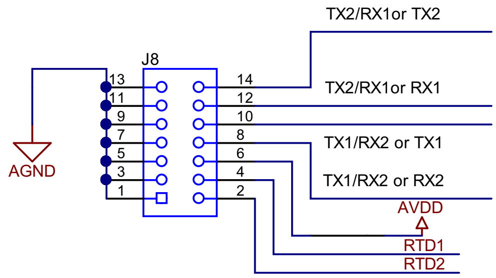


Figure 8. Socket (J8) Connecting Transmitting and Receiving Pins of TDC1000

3.

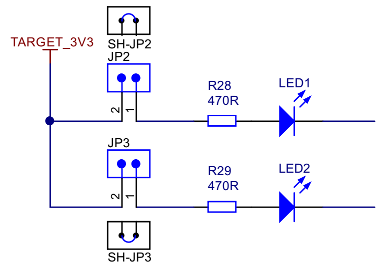


Figure 9. Jumpers JP2 and JP3 Connect Onboard LED

4. A slot of test pins for START and STOP pulses, VCOM, and the internal input of the comparator in the TDC1000.

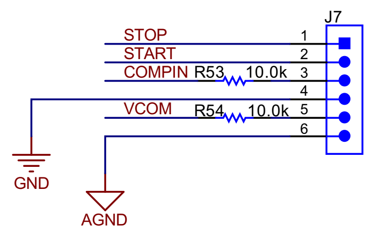


Figure 10. Test Pins of TDC1000

5. Pins 12 and 14 of this header are connected to the UART pin of the MCU. Use the latest MSP430 FET Tool with the UART feature to connect the board to the PC GUI. When using external power, the V_{CC} of the MCU has to be connected to pin 4 of the JTAG; the user can select either the TARGET_3V3 or VBAT.

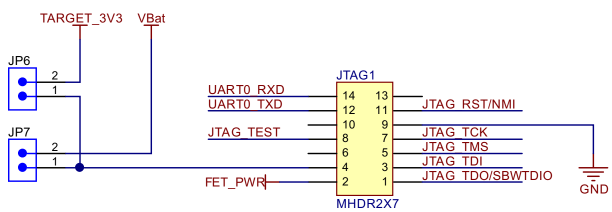


Figure 11. JTAG Interface for MSP430 FET Tool to Program MCU

6. This interface is compatible with the eZ-FET tool of the MSP430. Use the UART feature of the eZ-FET to connect the board to the PC GUI.

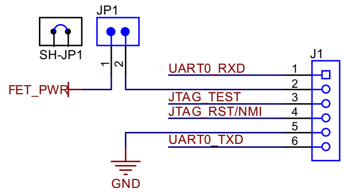


Figure 12. Spy-Bi-Wire and UART Interface

7. When using the eZ-FET tool and needing the power supplied from it, short this jumper and pins 1 and 2 of jumper J4 located in Part 11.

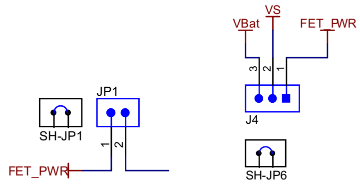


Figure 13. Jumper JP1

8.

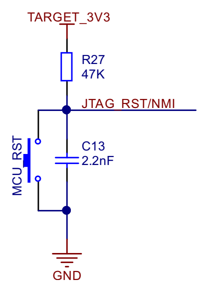


Figure 14. MCU Reset Button

9. Use these buttons to add on new features. There is no implementation for these buttons in the firmware. To operate this circuit: when a push button is pressed, it pulls the voltage of the "BUT_AN" to low to trigger an interrupt routine, which then switches on the ADC to measure the input voltage to determine which button is pressed.

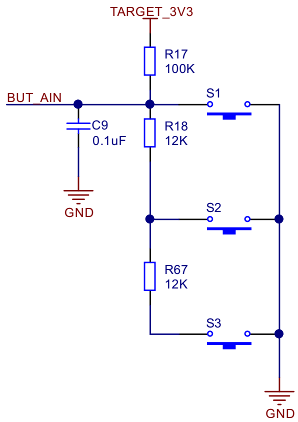


Figure 15. Three Push Buttons (Reserved for Future Use)

10. When battery is used, pins 2 and 3 of J4 are shorted with jumper and JP1 is opened.

    The jumper JP5 (see Figure 17) near the connector is to short the capacitor C17 to provide an always pull-up resistor to pin VSEL2 of the TPS62740, which will then output 2.0 V to start the MCU. Use it as an easy circuit setting of voltage selection during development of new firmware. To use this jumper, the MCU pin connecting to it has to be set as input mode. Once developed, remove the jumper to save current consumption.

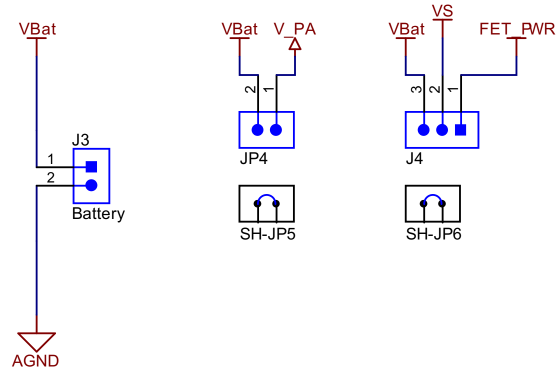


Figure 16. Battery Connector Using 3.6-V Lithium Battery

11. When connected to a battery, a low-power circuit consisting of C17 and R15 is used to provide a pulse to VSEL4, a selection pin of the TPS62740, to select an initial voltage of 2.6 V, which is high enough to start the MCU.

    In the initialization of the firmware, it has to select the proper operation voltage by using the selection pins.

    If all pins are pulled to low, the output voltage of 1.8 V may not be high enough to start the MCU. In this situation, short the input and output of the U3 (TPS62740) to supply 3.x V to the MCU and re-program it with proper firmware.

    There is a header (J6) connecting to each pin of U3.

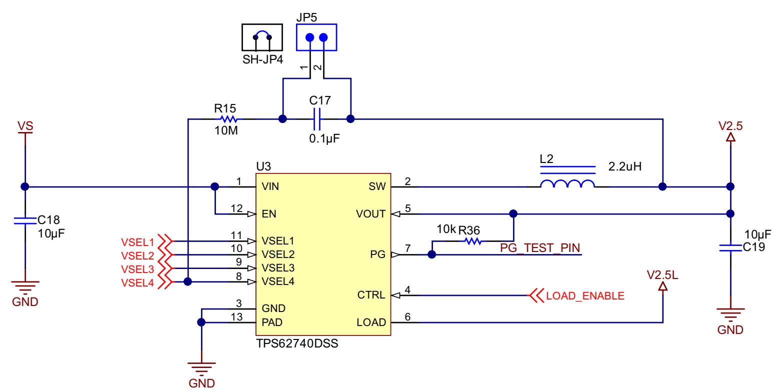


Figure 17. Buck Converter Using TPS62740 to Provide V_{CC} to the System

12. The firmware does not implement this part, as this is reserved for future use.

    A dedicated power supply for Part 14. When the communication module connecting to Part 14 is turned on, a large current will be given out by the super capacitor and the voltage will be stepped up to 3.3 V. The design will isolate the communication power from the system power. The design will not have current flowing from the system power to the module during its active state.

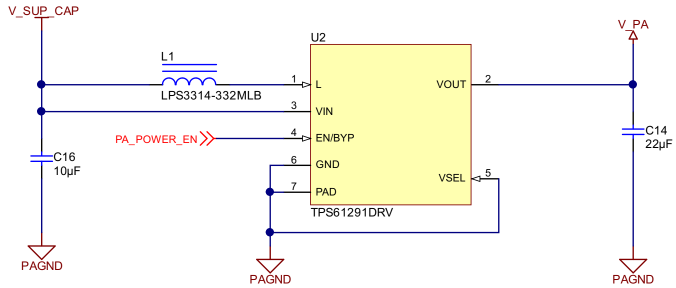


Figure 18. Boost Converter With Super Capacitor (in Part 13)

13. The firmware does not implement this part, as this is reserved for future use.

    Operation is as follows: A super capacitor, which is charged up from the battery through an npn switch and resistor (located in the middle of Part 14) to 2.5 V. This is done when the communication module connecting to Part 14 is in standby mode. When the module is in active mode, the npn switch will be turned off to isolate the battery power.

    There are two charging circuits. When the super cap is empty or with very little charges, "SLOW_CHARGE" is high and the circuit will charge up the super capacitor with current = (V2.5 – V_SUP_CAP) / 2.4k, which will limit the current to below 1 mA. This limitation is necessary, as the lithium battery has a limited current output.

    When the super cap is 0.1 V lower than V2.5, a resistor of 100 Ω is used instead of 2.4 K; the circuit is named "FAST_CHARGE". Every time a communication module is activated, it only consumes some charges in the super capacitor to lower its voltage within 0.1 V. Therefore, "FAST_CHARGE" will be used to re-charge the super-cap for the next communication use.

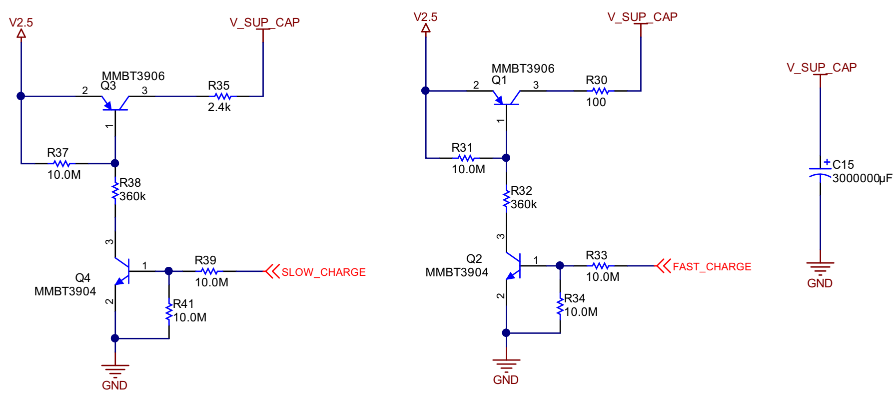


Figure 19. Resistive Charging Circuit for Super Capacitor

14. The socket has connection of SPI, UART and GPIO to the MCU. The user can also plug in an extension board to enhance the system features.

    The "V_PA" is the power supply for the power amplifier of the RF module. For testing, jumper JP4 (see Figure 16) is provided to direct connection to the DC or battery power supply.

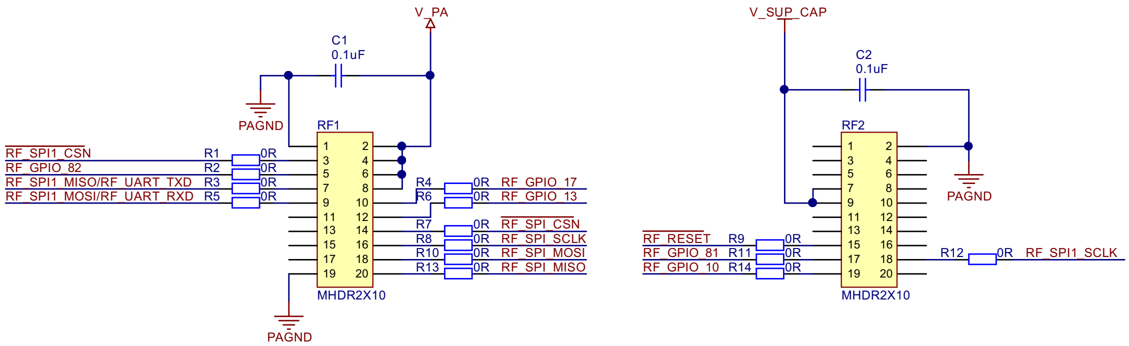


Figure 20. Socket for Connection of Communication Module (Wired or Wireless Type)

15. The core circuit of measurement on this TI design consists of the TDC1000, TDC7200 and an 8-MHz oscillator. Some important notes as follows have to be followed when implementing this circuit.

The ferrite in FB1 and FB2 with capacitors of 0.1 µF and 0.01 µF, respectively, are used to provide a low-noise DC power to the TDC1000. When implementing the low-power design, AVDD and VIO to the TDC1000 are connected together. From the datasheet, AVDD must be set to be equal to or higher than VIO; otherwise, a large current of a couple of mA will be drained. When in standby mode, both the TDC1000 and TDC7200 will be disabled by pulling low the enable pin.

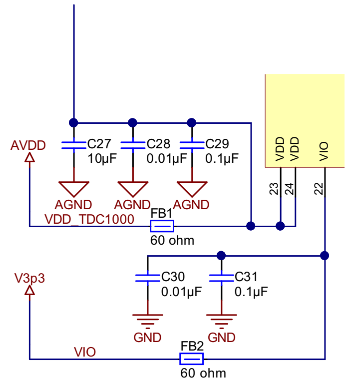


Figure 21. Low-Pass Filters for Power Supplies of TDC1000

The stability of VCOM is important for accurate measurement. 10 nF in C24 is used; by experiment, it is the most optimal value. The R52 is used as a reference resistor for measurement of temperature sensor PT500 / PT1000. The accuracy of this 1-KΩ resistor is 0.01%.

Resistors R40 and R57 are used to provide damping of ultrasonic transducers. With these resistors, the difference of differential time of flight among STOP1 to STOP5 is reduced.

The following circuit from "PGAOUT" to "COMPIN" is to provide a band pass filter with center frequency of 1 MHz to reduce noise of the received signal. As a result, the standard deviation of measurement data is reduced.

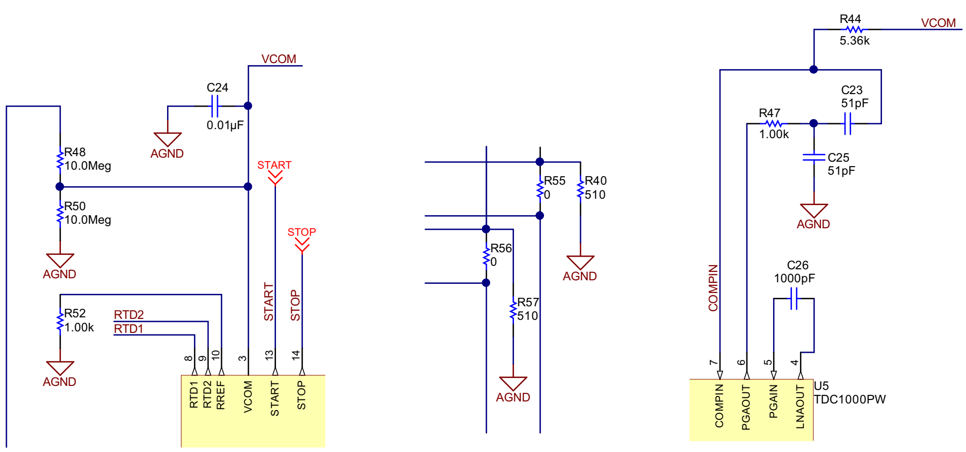
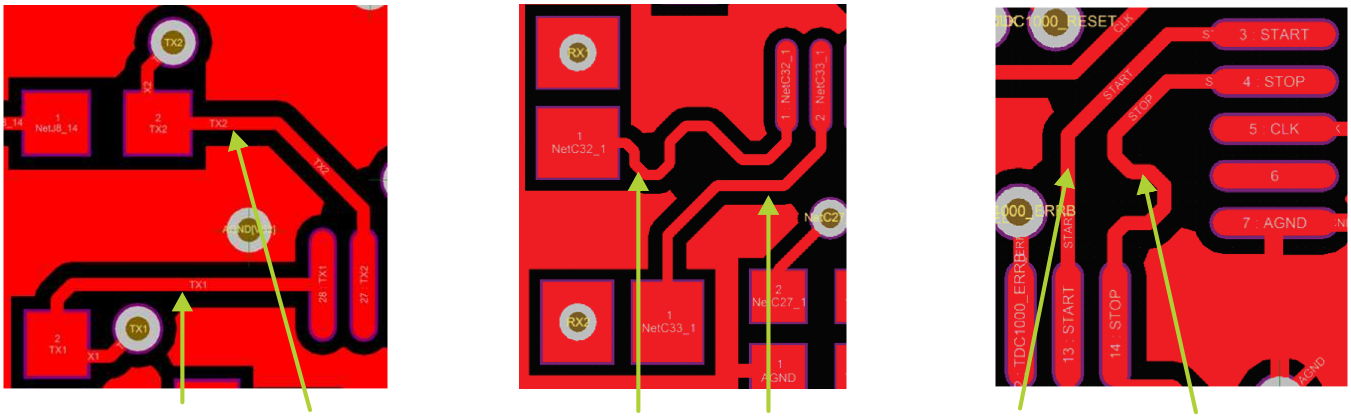


Figure 22. Critical External Passive Circuits of TDC1000

The R43 and R45 of 200 Ω have to be matched with each other within a 1% error; so for the capacitors C32 and C33. As the measurement on the differential time of flight is in unit of picosecond, to reduce offset value, the length of signal lines on transmitting end and receiving end have to be matched. For the same reason, the START and STOP signal lines need to be matched as well.



Matched TX1 and TX2 signal lines

Matched RX1 and RX2 signal lines

START and STOP signal lines are matched

Figure 23. PCB Layout of Matched Signal Lines

5 Software Description

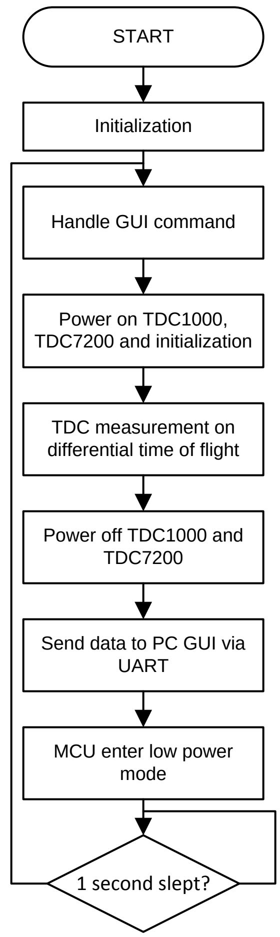


Figure 24. Software Flowchart

The software is designed to optimize the power consumption of the system. It starts with initializing the MCU peripherals and I/O ports. The flowchart shown in Figure 24 consists of the PC GUI operation. In the infinite loop of measurement, it checks the command from the GUI and then triggers the measurement. As the TDC1000 and TDDC7200 are powered off in standby mode, when they are powered on, the register setting has to be reloaded. The whole process of power on, measurement, and power off need a period of around 35 ms in which a large portion is the delay for stabilization of the system. After that, readings from the TDC7200 are sent to the GUI through UART. The MCU will enter into a low-power mode and wait for 1 second in default before the next cycle of measurement.

In the software, two modes can be selected. One mode is working with the GUI and another is without the GUI. The mode can be selected with "define GUI" in "global.h". Remark it to select non-GUI operation, which will use the minimum power consumption. For both GUI and NON-GUI operation, the LCD will display the differential time of flight.

6 PC GUI Operation

In the GUI, only five pages or TABs are used: SETUP, TDC1000, TDC7200, TOF_ONE_SHOT, and GRAPH. Raw data from the TDC7200 will be sent to the GUI and processed. There is no calculated result in the firmware.

In the SETUP tab, select the com port connecting to the board and click "CONNECT" to link the board and the PC GUI.

The triggering frequency is defaulted to 1 second in the firmware. The user can select the triggering frequency on this page. However, do not select 100 ms because there may not be enough time to synch the data stream/GUI command to the firmware and the GUI.

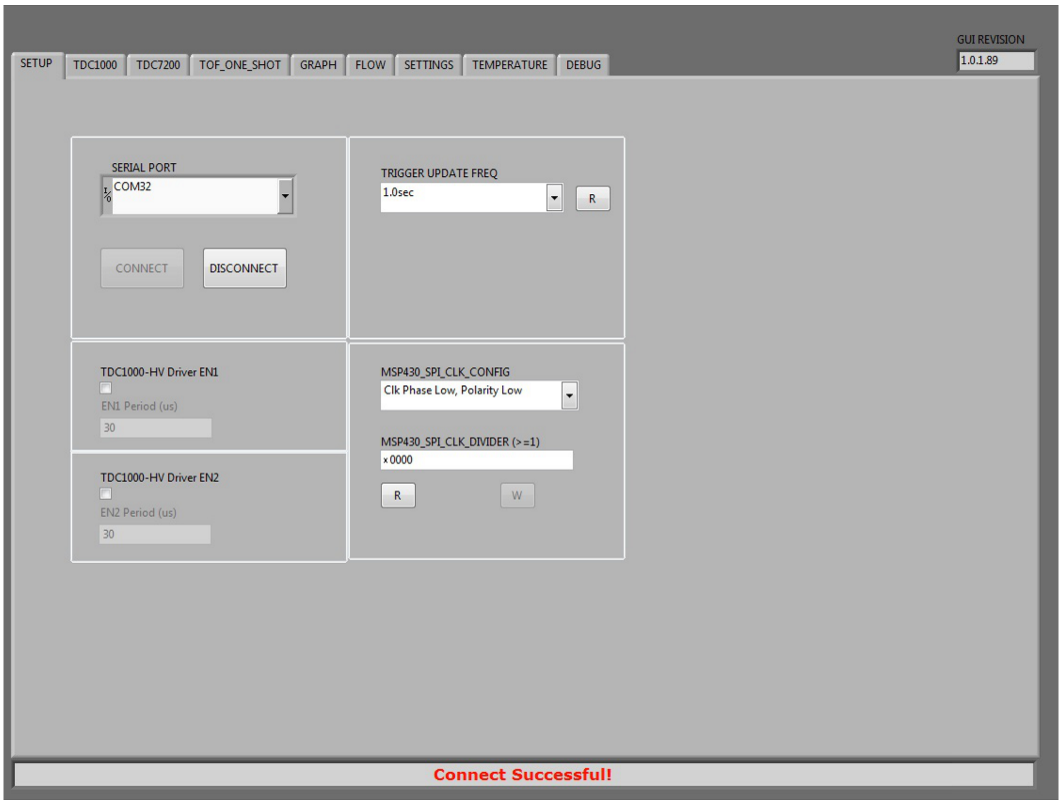


Figure 25. SETUP Settings

After SETUP, open the TAB of the TDC1000. In this page, click "READ ALL" to read the setting of the TDC1000. For the first time to power on the TDC1000, the default setting will be read.

The user can change the individual register setting according to the TDC1000 datasheet and save the whole configuration to the hard disk with "SAVE CONFIG". Load the configuration back to the TDC1000 with "LOAD CONFIG".

The "CONTINUOUS TRIGGER" command enables the signal output. The user can then see the real time effect of the setting by oscilloscope.

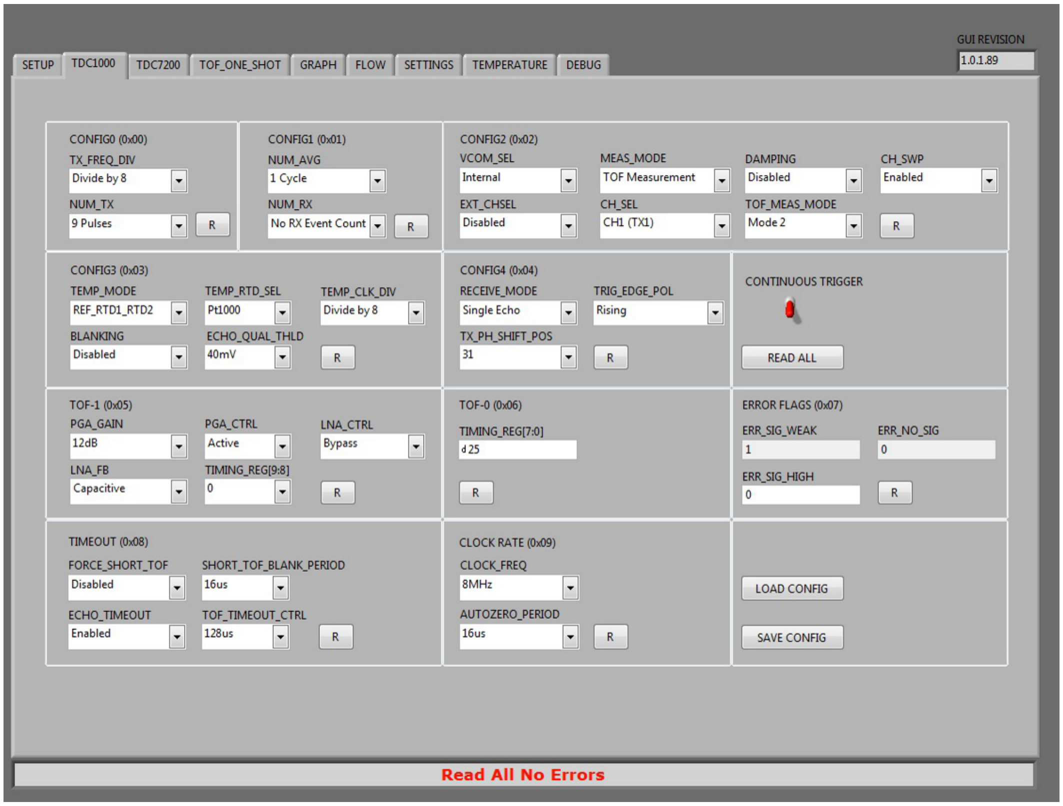


Figure 26. TDC1000 Settings

In the TAB of the TDC7200, the user can configure the register setting of the TDC7200. At the first time of power up and "READ ALL" is clicked, the default setting of TDC7200 is read.

The user can configure individual register settings according to the TDC7200 datasheet. "SAVE CONFIG" to save the setting into hard disk. "LOAD CONFIG" to load the setting from hard disk into the registers.

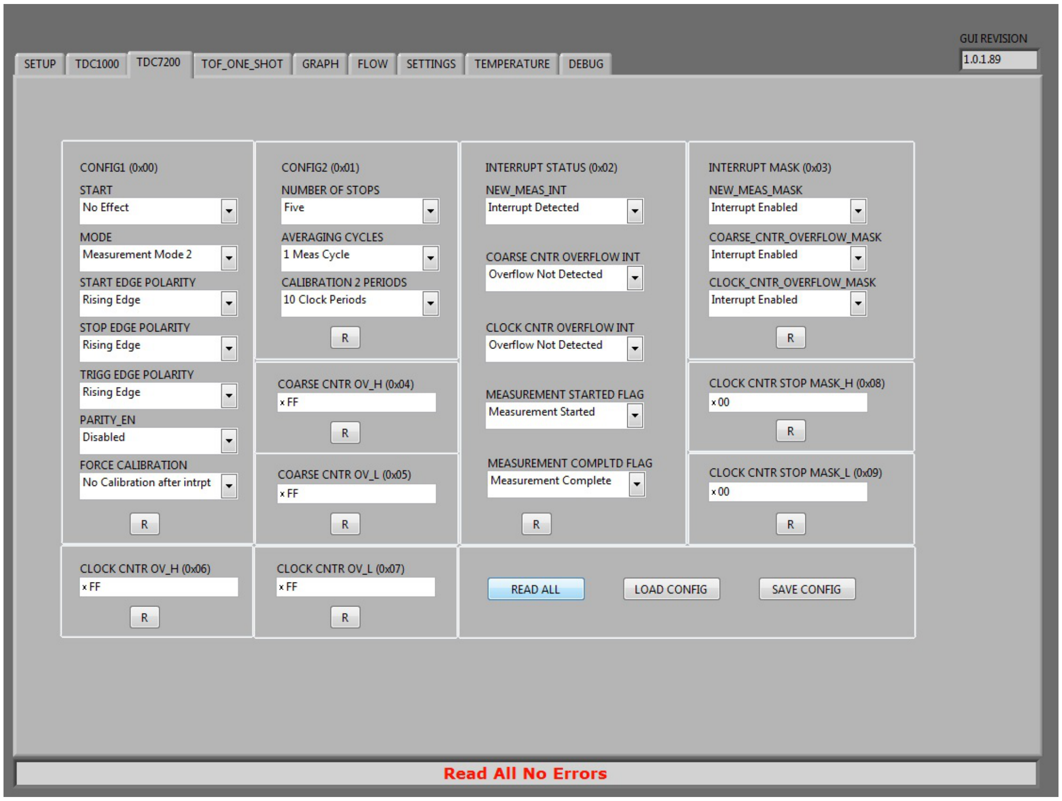


Figure 27. TDC7200 Settings

In the TAB of "TOF_ONE_SHOT", when the button "TOF_ONE_SHOT" is pressed, one set of measurement reading the TDC7200 will be fetched.

The calculated results in the GUI will be displayed on the "DEBUG OUT".

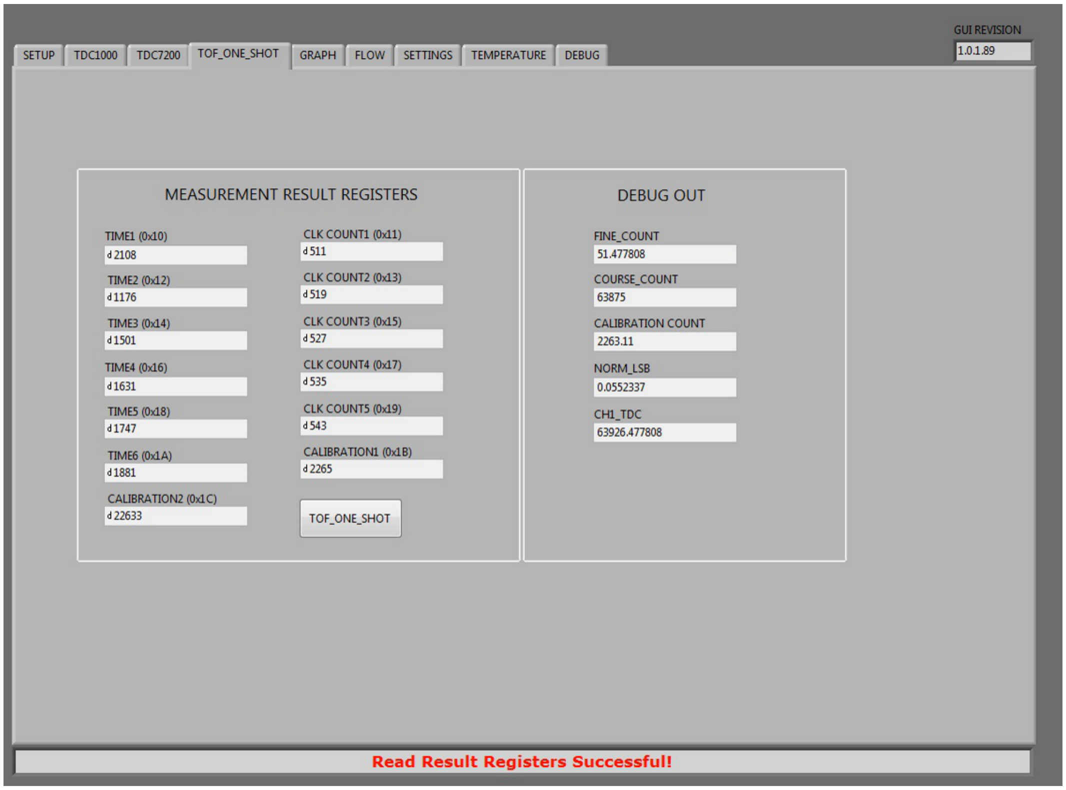


Figure 28. TOF_ONE_SHOT Settings

In the TAB of "GRAPH", it receives the streaming data from the TI design. After calculation, the result is displayed onto the monitor in black.

The GUI has the function of saving the graph data and records the register readings into a file. To enable this function, the corresponding check box is selected. When the "FLOW MODE" is checked, the differential time of flight will be displayed.

When the "FLOW MODE" is unchecked, the time of flight from the START pulse to the STOP pulse is displayed.

"TDC_SELECT" to select different STOP pulse, from STOP 1 to STOP 5 in "START GRAPH" is clicked to start the data logging. "STOP GRAPH" is to stop the data logging.

If the reading is out of scale, move the mouse cursor to the black monitor and right click. Select "Auto Scale Y" to auto scale the curve into the right position.

Figure 29. GRAPH Settings

7 Test Data

7.1 Test Setup to Measure Accuracy

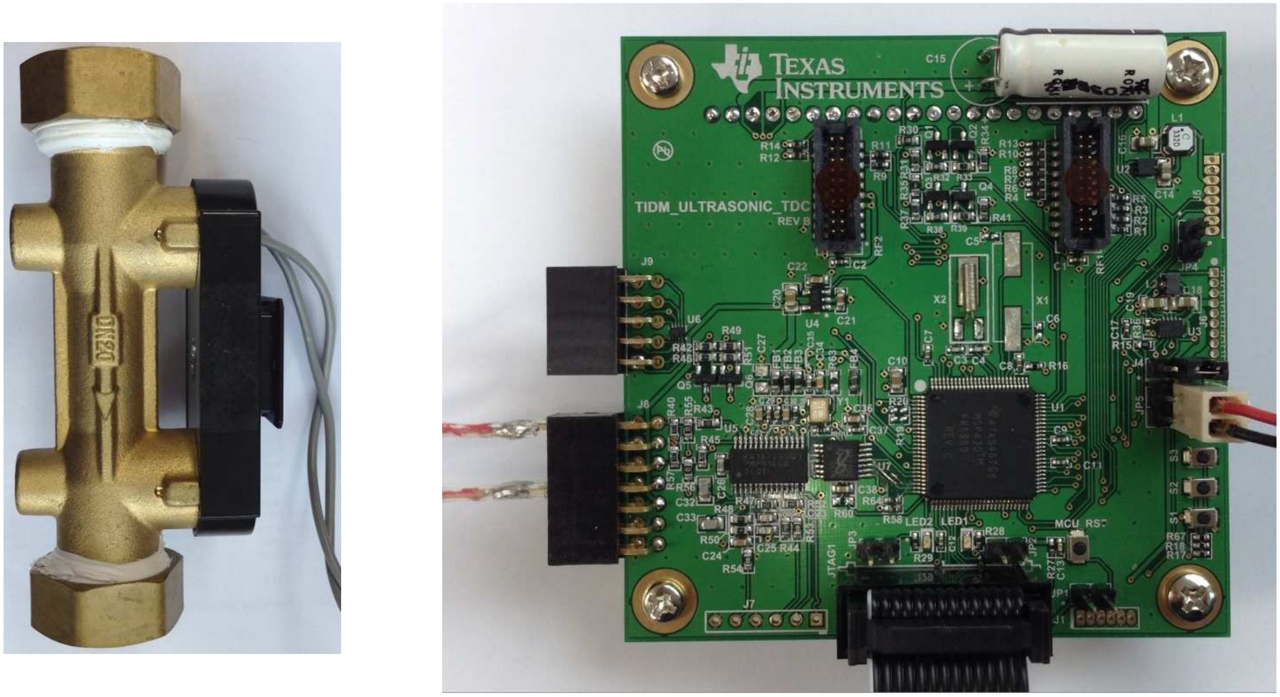


Figure 30. System Setup to Measure Accuracy of Differential Time of Flight

The setup includes an ultrasonic pipe filled with water connected to the board, as shown in Figure 30. The pipe is sealed at both ends without the flow of water to measure the accuracy of the differential time of flight of the system. The procedure is as follows:

1. Remove all jumpers.
2. Connect pin 2 and 3 of J4.
3. Connect ultrasonic transducers in a pipe filled with water to J8.
4. Connect UART in JTAG interface, or using UART connection in J1
5. Plug in the 3.6-V DC supply to J3.
6. Switch on the DC power supply.
7. Program it using Code Composer Studio™ (CCS) 6.1, with the firmware which defines PC GUI by using "#define OPERATION_MODE 2" in "global.h". After that, exit CCS.
8. Press the MCU reset button to ensure a restart of the firmware.
9. Open the PC GUI.
10. Select the proper COM port in SETUP page of the GUI and click "CONNECT".
11. Select "1 second" as triggering frequency.
12. In TDC1000 TAB, click "READ ALL" to load the default setting from the firmware.
13. In TDC7200 TAB, click "READ ALL" to load the default setting from the firmware.
14. In the "GRAPH" TAB, check "FLOW MODE" to measure the differential time of flight.
15. Check the box of "SAVE RESULT REGR TOFILE".
16. Click "START GRAPH".
17. A window is displayed. Enter the file name of the file and click "OK".
18. Wait for five minutes and click "Stop Graph".
19. Process the data of the file using Microsoft® Excel®.

7.2 Test Setup to Measure Current Consumption

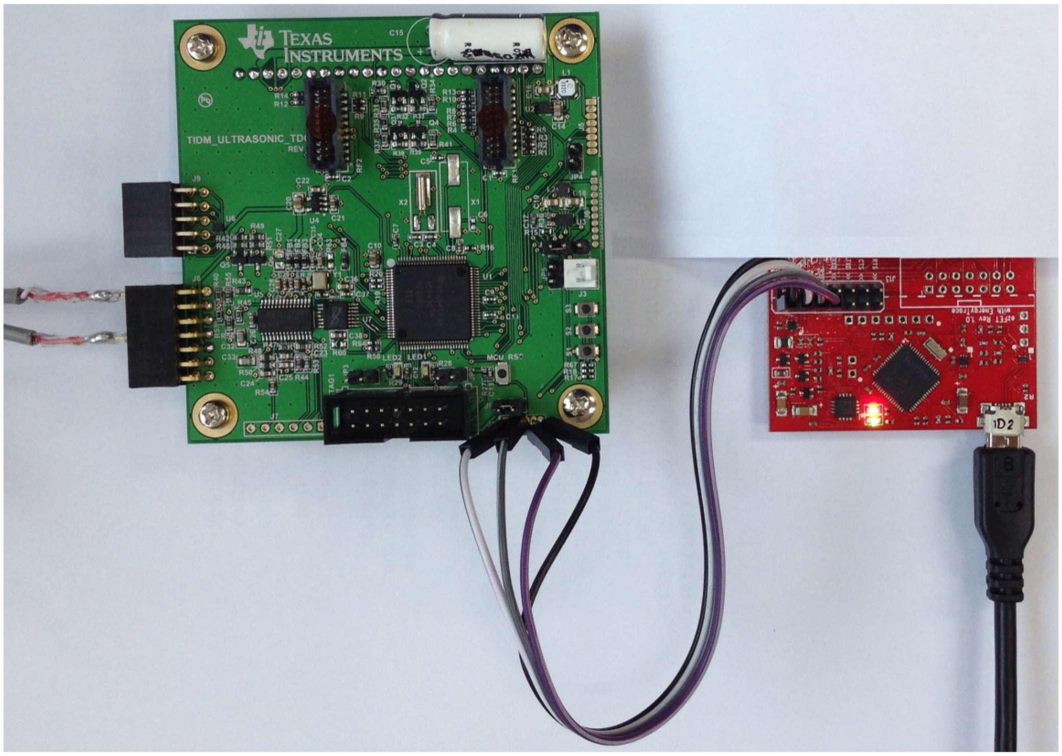


Figure 31. System Setup to Measure of Current Consumption

This setup uses an eZ-FET tool with EnergyTrace™ module to monitor the energy consumption of the TI design. This tool uses a Spy-Bi-Wire connection. The UART has to be disconnected to avoid current leakage. This setup includes an ultrasonic pipe filled with water connected to the board. The setup procedure is as follows:

1. Remove all jumpers, DC power, and JTAG connection.
2. Short the jumper JP1 and short pin 1 and 2 of J4.
3. Connect the Spy-Bi-Wire from the eZ-FET to J1 on the board, without connecting the UART pins.
4. Connect eZ-FET to PC.
5. Program the it using CCS 6.1, with the firmware without PC GUI and LCD, by using "#define OPERATION_MODE 1" in "global.h".
6. Compile and enter debug mode of CCS.
7. In the "EnergyTrace" setting panel in CCS 6, set 10 second as the measurement duration.
8. Select "Run" in menu bar and click "Free Run".
9. Click the "Energy" tab in "EnergyTrace" panel.
10. The user can see a large surge of energy in the beginning of initialization of the firmware.
11. Press "ALT + F8" to suspend the program.
12. Select "Run" in menu bar and click "Free Run" again.
13. The energy consumption in steady state is shown on the "EnergyTrace" monitor.
14. Click the "EnergyTrace Technology" tab to read the energy consumption and supply voltage. With this data, the average current consumption can be calculated.

8 Test Results

The test results for accuracy are shown in Figure 32 and Figure 33. Figure 32 shows the plot of the differential time of flight for each STOP pulse over five minutes time, with one measure per second. Figure 33 shows the average of these five curves. Table 1 shows the mean value and the standard deviation of the results.

From Table 1, the mean value is supposed to be zero for a zero flow rate. However, it comes out as a significant figure. This difference is due to the imbalance of transducers and unmatched value of the front end components. As it represents a zero flow, the mean value can be treated as an offset in the calculation of the flow rate.

The standard deviation for each STOP is ranged from 134 to 241 ps, while that of the averaged data is only 126 ps. Implement a higher accuracy system by taking a couple of measures per second and perform averaging technique to reduce error (standard deviation).

Table 1. Mean and Standard Deviation of the Test Results

DIFFERENTIAL TOF	MEAN VALUE	STANDARD DEVIATION
STOP1	–2.934 ns	241 ps
STOP2	–2.928 ns	205 ps
STOP3	–2.521ns	153 ps
STOP4	–2.200 ns	134 ps
STOP5	–1.806 ns	157 ps
Averaged curve	–2.478 ns	126 ps

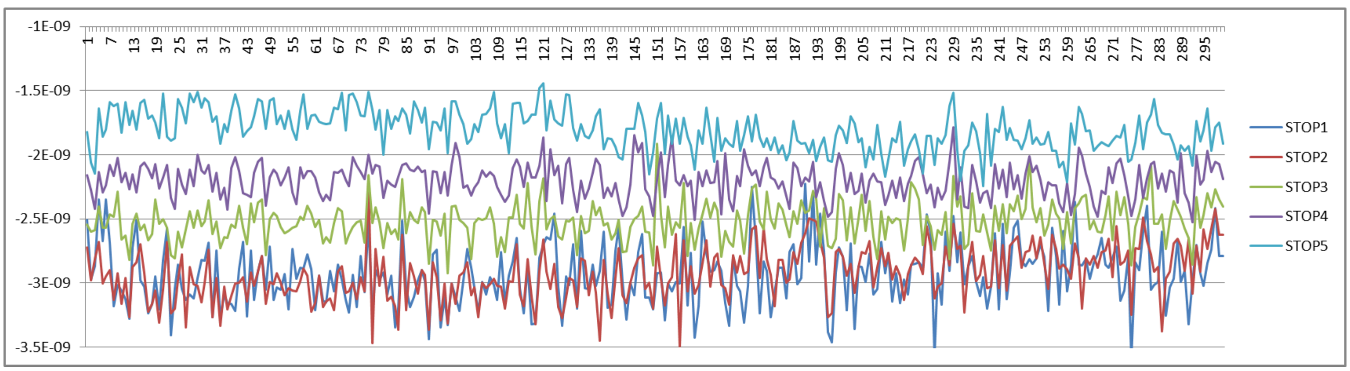


Figure 32. Test Results of Five STOPs

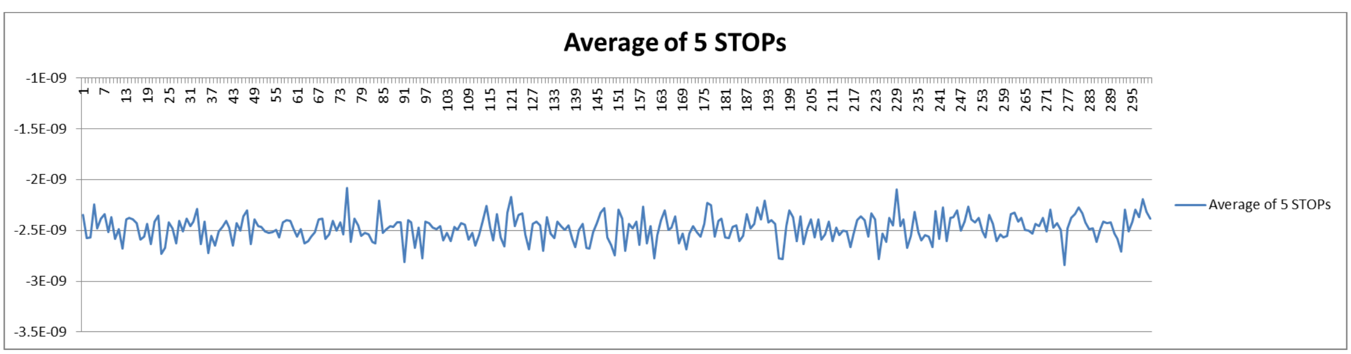


Figure 33. Test Results of the Average of Five STOPs

Figure 34 shows the pattern of energy consumption. A low power mode with a system voltage of 2.5 V is the normal state. When a one-second time interval is reached, the MCU sets the system voltage to 3.3 V and wakes up the system for measurement. During the active period of 2.2 ms, a comparatively large current is consumed, which reflects in a step increment in the energy consumption in the graph. After measurement, the MCU switches off the system to low power mode and set the voltage to 2.5 V from 3.3 V. During this state, the charges in the output capacitor of the TPS62740 provide the current intake of the system, which almost does not need any extra charges from the supply and so the curve is flat.

The calculation of average current is as follows:

The total energy consumed in 10 seconds = 375 µJ
The voltage supply from the eZ-FET is 3.58 V
Therefore the average current consumption = 375 / 10 / 3.58 = 10.5 µA

Figure 34. Energy Consumption of TI Design

9 Design Files

9.1 Schematics

To download the schematics, see the design files at TIDM-ULTRASONIC-FLOW-TDC.

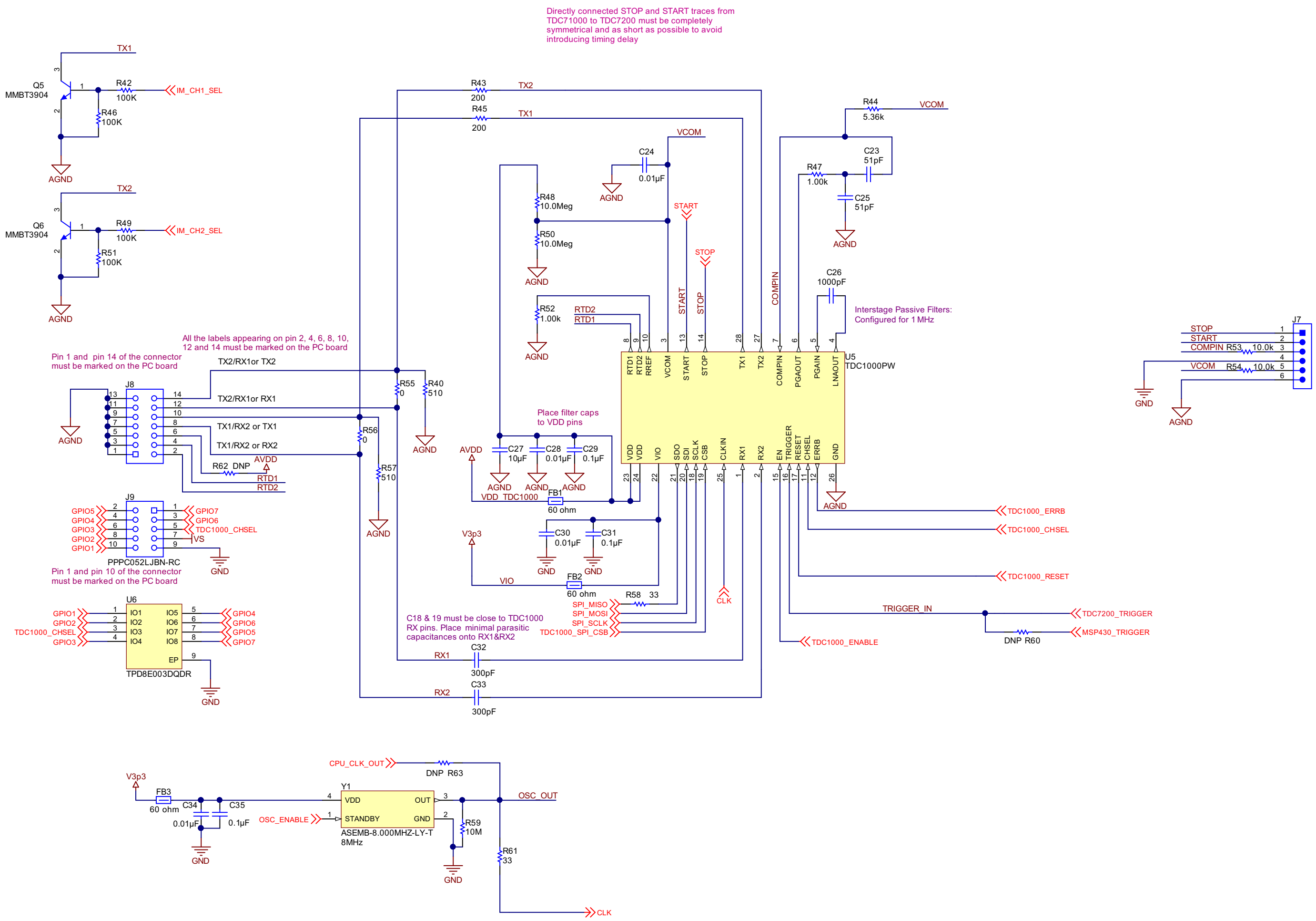
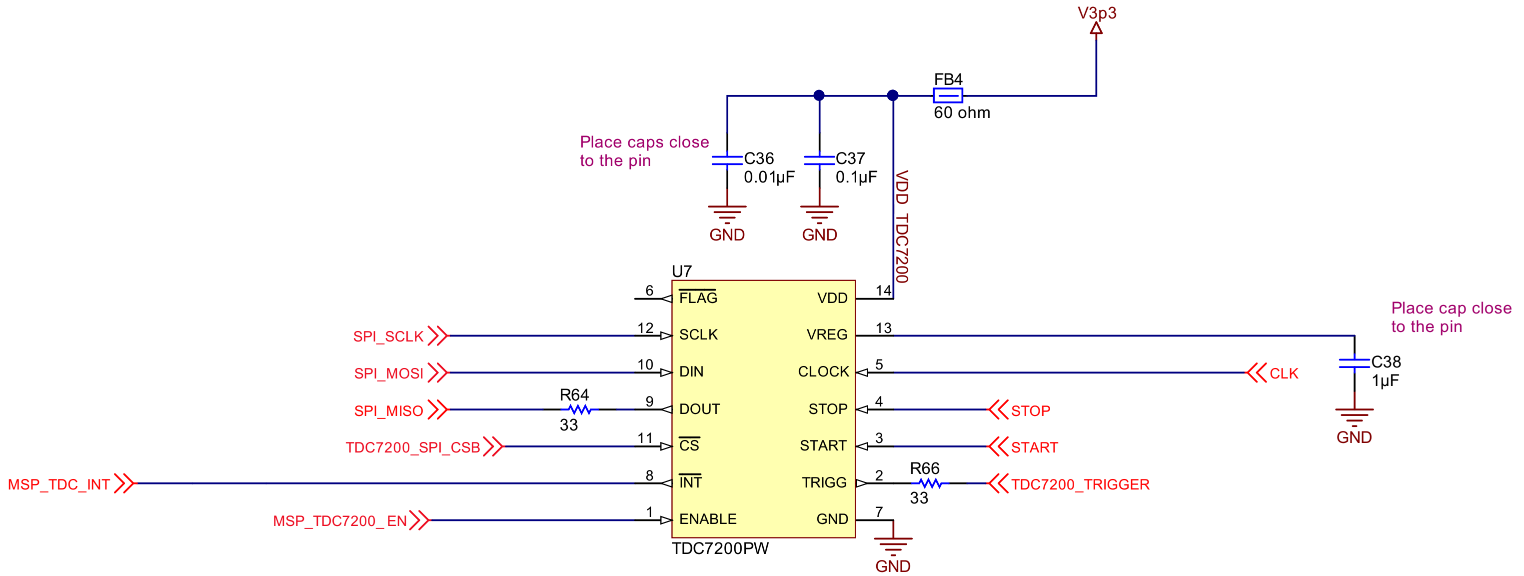


Figure 35. TDC1000 Schematic



Component value = DNP means do not populate

Figure 36. TDC7200 Schematic

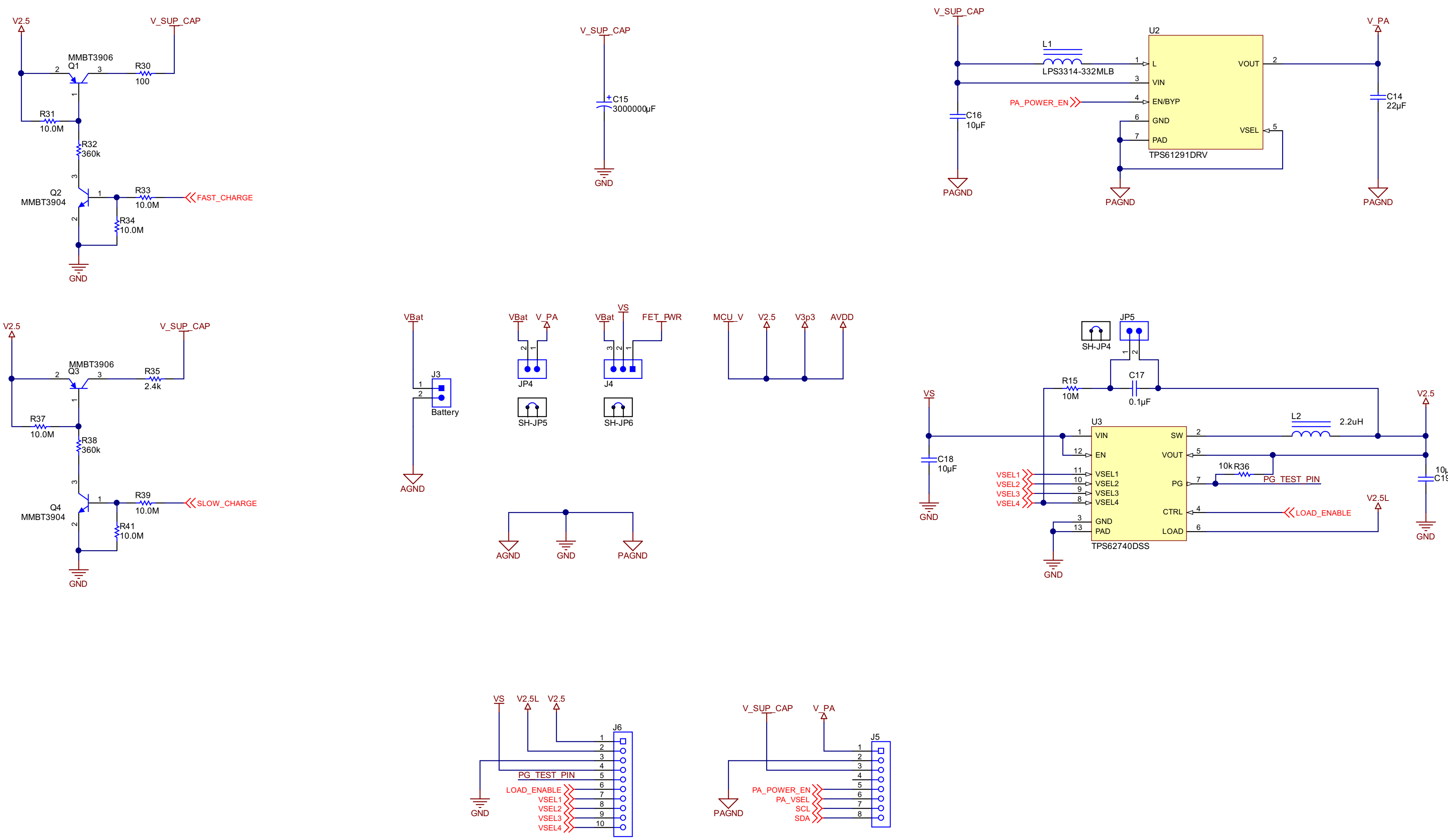


Figure 37. Power Circuit Schematic

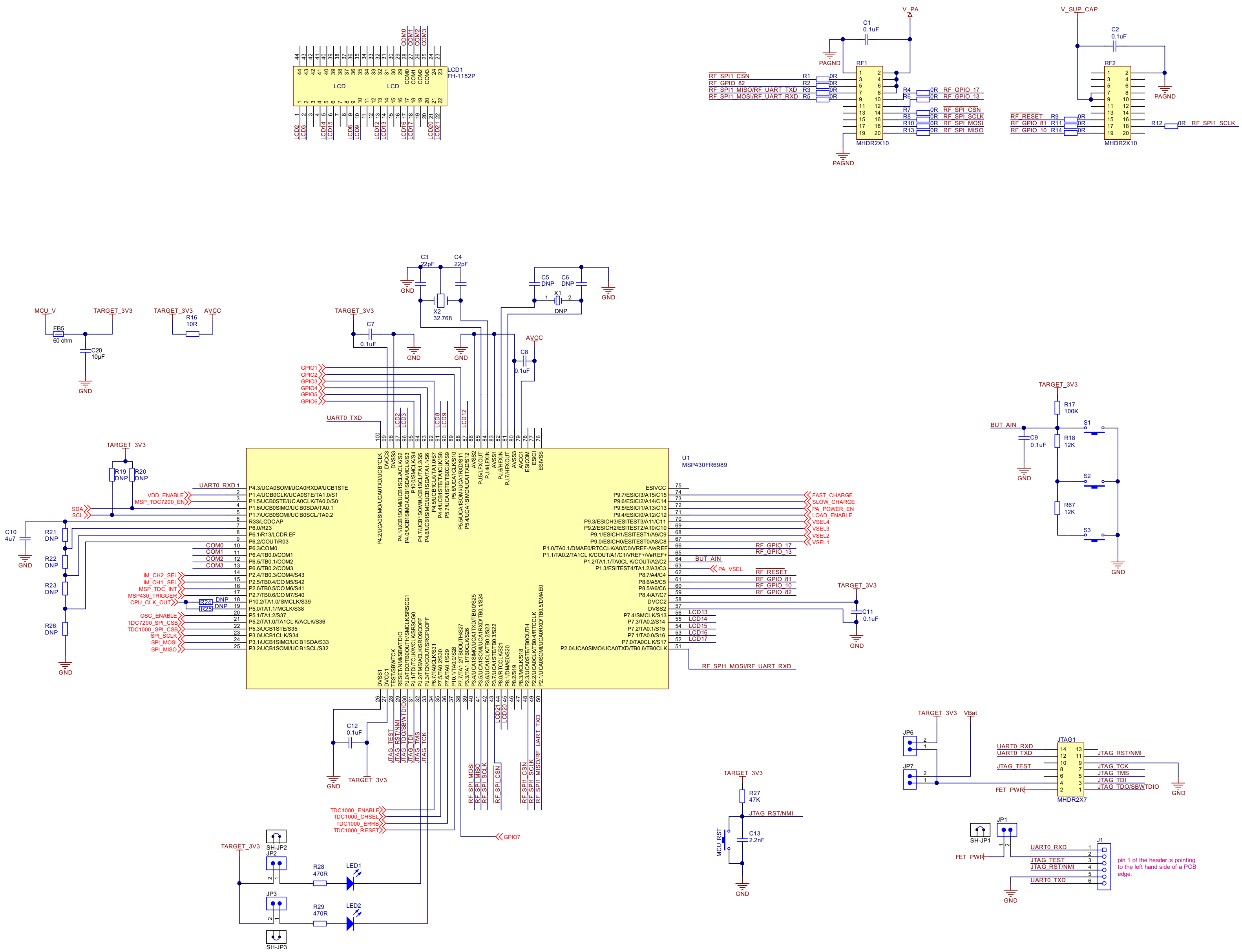


Figure 38. MCU Circuit Schematic

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDM-ULTRASONIC-FLOW-TDC.

Table 2. BOM

DESIGNATOR	VALUE	QTY	DESCRIPTION	FOOTPRINT	MANUFACTURER	LIBREF
C1, C2, C3, C4, C5, C6, C7, C8, C9, C11, C12, C13, R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R12, R13, R14, R16, R17, R18, R21, R22, R23, R24, R25, R26, R27, R28, R29, R67	0.1uF, 0.1uF, 22pF, 22pF, DNP, DNP, 0.1uF, 0.1uF, 0.1uF, 0.1uF, 0.1uF, 2.2nF, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 0R, 10R, 100K, 12K, DNP, DNP, DNP, DNP, DNP, DNP, 47K, 470R, 470R, 12K	39	Capacitors and Resistors	402		Cap, Res2
C10	4u7	1	Capacitor	805		Cap
C14	22uF	1	CAP, CERM, 22 µF, 6.3 V, +/- 20%, X5R, 0805	0805_HV	MuRata	GRM21BR60J226ME39L
C15	3000000uF	1	CAP, Electric Double Layer, 3000000 µF, 2.7 V, +20/-10%, 0.061 ohm, TH	ESHSR_800x2000	NESSCAP	ESHSR-0003C0-002R7
C16	10uF	1	CAP, CERM, 10 µF, 10 V, +/- 10%, X5R, 0805	0805_HV	MuRata	GRM219R61A106KE44D
C17	0.1uF	1	CAP, CERM, 0.1 µF, 6.3 V, +/- 10%, X5R, 0402	402	TDK	C1005X5R0J104K
C18, C19, C20, C27	10uF	4	CAP, CERM, 10 µF, 10 V, +/- 10%, X7R, 0805	0805_HV	MuRata	GRM21BR71A106KE51L
C34, C36	0.01uF	2	CAP, CERM, 0.01uF, 25V, +/- 10%, X7R, 0603	603	MuRata	GRM188R71E103KA01D
C23, C25	51pF	2	CAP, CERM, 51pF, 100V, +/- 5%, C0G/NP0, 0603	603	MuRata	GRM1885C2A510JA01D
C24	0.01uF	1	CAP, CERM, 0.01uF, 25V, +/- 5%, C0G/NP0, 0603	603	TDK	C1608C0G1E103J
C26	1000pF	1	CAP, CERM, 1000 pF, 50 V, +/- 5%, C0G/NP0, 0603	603	TDK	C1608C0G1H102J
C28, C30	0.01uF	2	CAP, CERM, 0.01uF, 10V, +/- 10%, X5R, 0402	402	MuRata	GRM155R61A103KA01D
C29, C31, C35, C37	0.1uF	4	CAP, CERM, 0.1uF, 10V, +/- 10%, X5R, 0402	402	TDK	C1005X5R1A104K
C32, C33	300pF	2	CAP, CERM, 300pF, 50V, +/- 5%, C0G/NP0, 0603	805	MuRata	GRM1885C1H301JA01D
C38	1uF	1	CAP, CERM, 1uF, 25V, +/- 10%, X7R, 0603	603	MuRata	GRM188R71E105KA12D

Table 2. BOM (continued)

DESIGNATOR	VALUE	QTY	DESCRIPTION	FOOTPRINT	MANUFACTURER	LIBREF
FB1, FB2, FB3, FB4, FB5	60 ohm	4	0.8A Ferrite Bead, 60 ohm @ 100MHz, SMD	603	Taiyo Yuden	BK1608HS600-T
H5, H6, H7, H8		4	Standoff, Hex, 0.5"L #4-40 Nylon	Keystone_1902 C	Keystone	1902C
J1		1	Receptacle, 50mil, 6x1, Gold, TH	Mill-Max_851-XX-006-10-001000	Mill-Max	851-43-006-10-001000
J3		1	Header (friction lock), 100mil, 2x1, Tin, TH	MOLEX_22-27-2021	Molex	22-27-2021
J4		1	Header, 100mil, 3x1, Gold, TH	TSW-103-07-G-S	Samtec	TSW-103-07-G-S
J5		1	Receptacle, 50 mil, 8x1, Gold, R/A, TH	Mill-Max_851-43-008-20-001000	Mill-Max	851-43-008-20-001000
J6		1	Receptacle, 50mil, 10x1, Gold, R/A, TH	CONN_851-43-010-20-001000	Mill-Max	851-43-010-20-001000
J7		1	Header, 100mil, 6x1, TH	Mill-Max_800-10-006-10-001000	Mill-Max	800-10-006-10-001000
J8		1	Receptacle, 7x2, 2.54mm, R/A, TH	SSW-107-02-G-D-RA	Samtec	SSW-107-02-G-D-RA
J9		1	Connector, Receptacle, 100mil, 5x2, Gold plated, R/A, TH	CONN_PPPC0 52LJBN-RC	Sullins Connector Solutions	PPPC052LJBN-RC
JP1, JP2, JP3, JP4, JP5, JP6, JP7		5	Header, TH, 100mil, 2x1, Gold plated, 230 mil above insulator	TSW-102-07-G-S	Samtec	TSW-102-07-G-S
JTAG1		1	Header, 7-Pin, Dual row	2X7BOXHEAD ER		MHDR2X7
L1	3.3uH	1	Inductor, Shielded Drum Core, Ferrite, 3.3uH, 1.3A, 0.14 ohm, SMD	LPS3314	Coilcraft	LPS3314-332MLB
L2	2.2uH	1	Inductor, Shielded, Ferrite, 2.2uH, 0.97A, 0.056 ohm, SMD	IND_VLF25201 5	TDK	VLF252015MT-2R2M
LCD1		1		FH-1152P		FH-1152P
LED1, LED2		2	Typical RED, GREEN, YELLOW, AMBER GaAs LED	LED_LTST-C190		LED2
MCU_RST, S1, S2, S3		4	Switch	B3U-1000P		SW-PB
Q1, Q3	0.25V	2	Transistor, PNP, 40V, 0.2A, SOT-23	SOT-23	Fairchild Semiconductor	MMBT3906, Fairchild Semiconductor

Table 2. BOM (continued)

DESIGNATOR	VALUE	QTY	DESCRIPTION	FOOTPRINT	MANUFACTURER	LIBREF
Q2, Q4, Q5, Q6	0.2V	4	Transistor, NPN, 40V, 0.2A, SOT-23	SOT-23	Fairchild Semiconductor	MMBT3904, Fairchild Semiconductor
R15, R59	10Meg	1	RES, 10 M, 5%, 0.063 W, 0402	402	Vishay-Dale	CRCW040210M0 JNED
R19, R20		2	Resistor	402		Res2
R30	100	1	RES, 100, 5%, 0.1 W, 0603	603	Vishay-Dale	CRCW0603100R JNEA
R31, R33, R34, R37, R39, R41, R48, R50	10.0Meg	8	RES, 10.0 M, 1%, 0.1 W	603	Vishay-Dale	CRCW060310M0 FKEA
R42, R46,R49, R51	100k	4	RES, 100K, 5%, 0.1 W	603	Vishay-Dale	CRCW0603100K JNEA
R32, R38	360k	2	RES, 360 k, 5%, 0.1 W, 0603	603	Vishay-Dale	CRCW0603360K JNEA
R35	2.4k	1	RES, 2.4 k, 5%, 0.1 W, 0603	603	Vishay-Dale	CRCW06032K40 JNEA
R36	10k	1	RES, 10 k, 5%, 0.063 W, 0402	402	Vishay-Dale	CRCW040210K0 JNED
R40, R57	510	2	RES, 510, 0.1%, 0.1 W, 0603	603	Susumu Co Ltd	RG1608P-511-B-T5
R43, R45	200	2	RES, 200 ohm, 0.1%, 0.1W, 0603	603	Susumu Co Ltd	RG1608P-201-B-T5
R44	5.36k	1	RES, 5.36k ohm, 1%, 0.1W, 0603	603	Vishay-Dale	CRCW06035K36 FKEA
R52	1.00K	1	RES, 1.00k ohm, 0.01%, 0.1W, 0603	603	DigiKey PN	RNCF0603TKY1 K00CT-ND
R47	1.00k	1	RES, 1.00k ohm, 1%, 0.1W, 0603	603	Vishay-Dale	CRCW06031K00 FKEA
R53, R54	10.0k	2	RES, 10.0k ohm, 1%, 0.1W, 0603	603	Yageo America	RC0603FR-0710KL
R55, R56, R62, R60, R63	0, 0, 0, DNP, DNP	5	RES, 0 ohm, 5%, 0.1W, 0603	603	Vishay-Dale	CRCW06030000 Z0EA
R58, R61, R64, R66	33	4	RES, 33 ohm, 5%, 0.063W, 0402	402	Vishay-Dale	CRCW040233R0 JNED
RF1, RF2		2	Header, 10-Pin, Dual row	TFM-110-02-SM-D-A-K		MHDR2X10
SH-JP1, SH-JP2, SH-JP3, SH-JP4, SH-JP5, SH-JP6	1x2	6	Shunt, 100mil, Gold plated, Black	SNT-100-BK-G	3M	969102-0000-DA
U1		1	MCU	MSP430FR698 9		MSP430FR698X PZ
U2		1	LOW Iq BOOST CONVERTER WITH BYPASS OPERATION, DRV0006A	DRV0006A	Texas Instruments	TPS61291DRV
U3		1	360nA IQ Step Down Converter for Low Power Applications, DSS0012A	DSS0012A	Texas Instruments	TPS62740DSS

Table 2. BOM (continued)

DESIGNATOR	VALUE	QTY	DESCRIPTION	FOOTPRINT	MANUFACTURER	LIBREF
U5		1	TDC1000 Precision AFE for Time of Flight, PW0028A	PW0028A_N	Texas Instruments	TDC1000PW
U6		1	ESD Array For Portable Space-Saving Applications, 8 Channels, -40 to +85 degC, 8-pin WSON (DQD), Green (RoHS & no Sb/Br)	DQD0008A	Texas Instruments	TPD8E003DQDR
U7		1	STOPWATCH IC FOR TIME MEASUREMENT BETWEEN TWO EVENTS, PW0014A	PW0014A_N	Texas Instruments	TDC7200PW
X2		1	Crystal, 32.768, 12.5pF, SMD	Cylindrical		CMR200T-32.768KDZFT
Y1		1	OSC, 8 MHz, 1.8 - 3.3V, SMD	3.2 x 2.5 x 1.05mm	Epson PG-310 8MHz	RS Alt: 667-6353
H1, H2, H3, H4		4	Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	NY PMS 440 0025 PH	B&F Fastener Supply	NY PMS 440 0025 PH

9.3 PCB Layout

To download the layer plots, see the design files at TIDM-ULTRASONIC-FLOW-TDC.

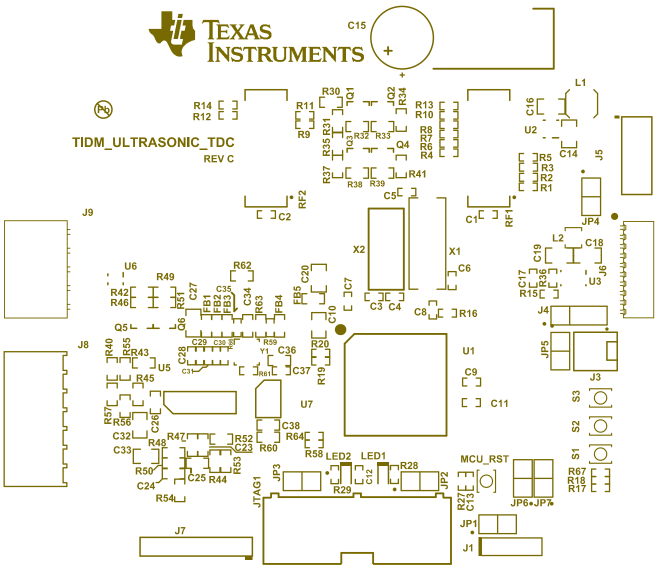


Figure 39. Top Overlay

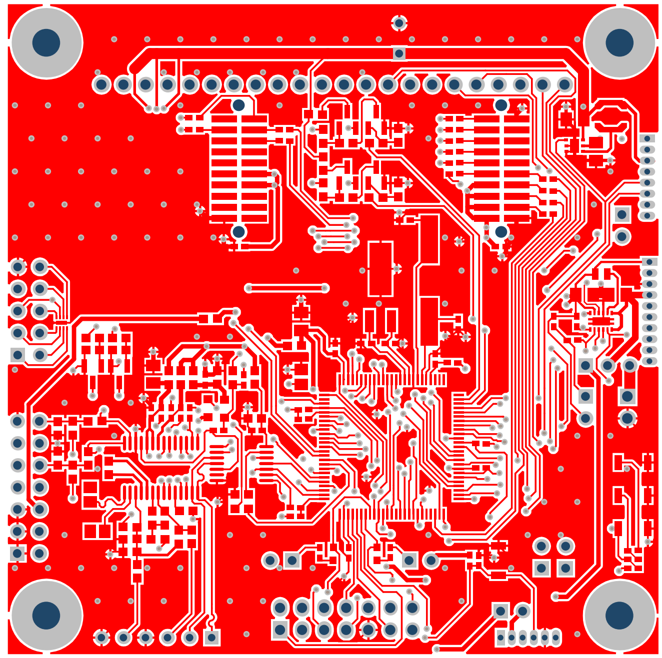


Figure 40. Top Layer

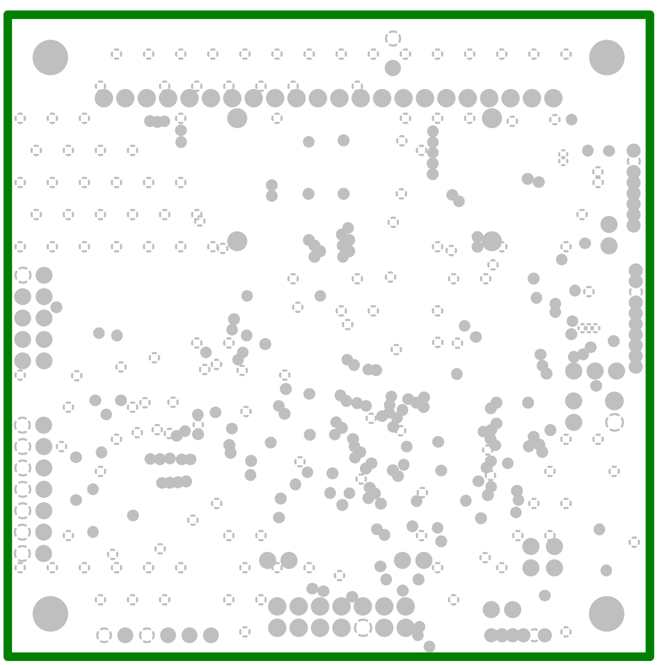


Figure 41. Internal Plane 1

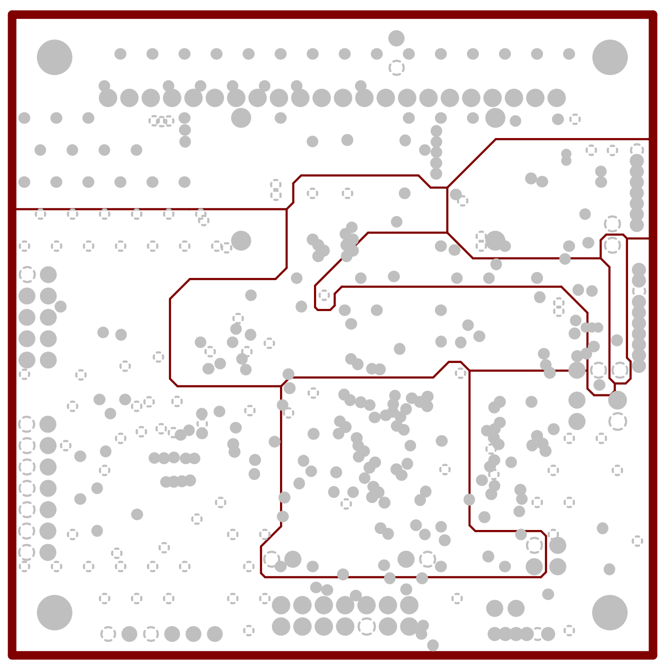


Figure 42. Internal Plane 2

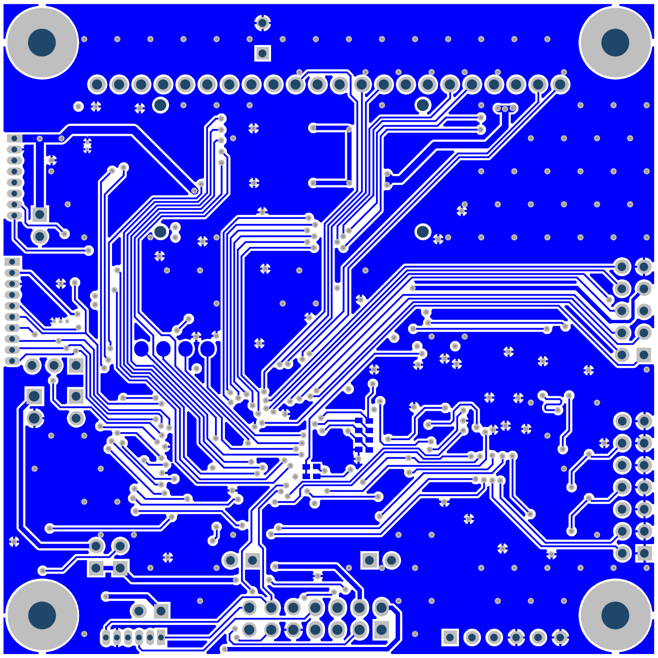


Figure 43. Bottom Layer

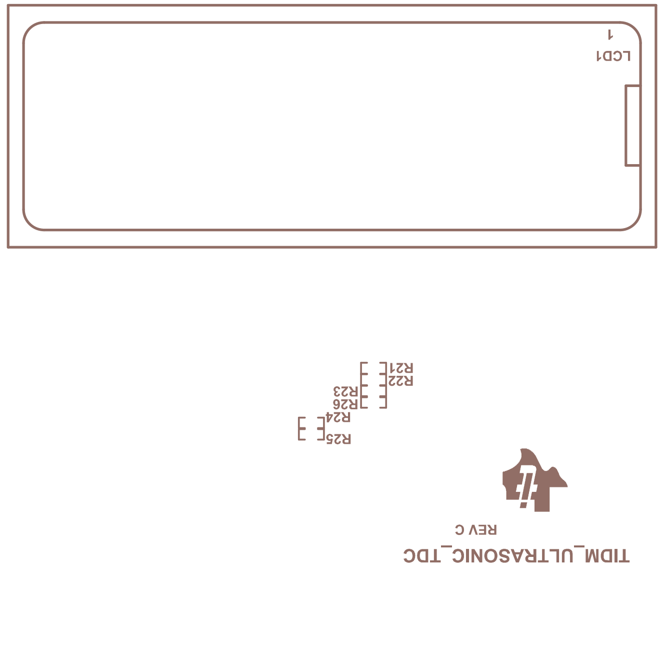


Figure 44. Bottom Overlay

9.4 Altium Project Files

To download the Altium project files, see the design files at TIDM-ULTRASONIC-FLOW-TDC.

9.5 Gerber Files

To download the Gerber files, see the design files at TIDM-ULTRASONIC-FLOW-TDC.

9.6 Software Files

To download the software files, see the design files at TIDM-ULTRASONIC-FLOW-TDC.

9.7 RF Modules

For more information on RF modules, contact Milen Stefanov at m-stefanov@ti.com.

10 About the Author

THOMAS KOT is a system and solutions architect in the Smart Grid and Energy group at Texas Instruments, where he primarily works on the flow meter reference design development and customer support. Thomas received his bachelor of engineering in electronic engineering from Hong Kong Polytechnic University in 1995 and received his master of science in electronic and information engineering from the same university in 2005. He received the master of business administration from City University of Hong Kong in 2007. Contact Thomas at thomas-kot@ti.com.

Revision History

Changes from Original (May 2015) to A Revision **Page**

- Changed title from *Ultrasonic TDC Flowmeter Reference Design* 1

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

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