

# ***LC Sensor Rotation Detection With MSP430™ Extended Scan Interface (ESI)***

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## **ABSTRACT**

This application report describes the implementation of a flow meter using the Texas Instruments MSP430FR6989 microcontroller with the Extended Scan Interface (ESI) module. This module can provide a contactless sensing approach to detecting a rotating disc. The number of rotations of the disc indicates the volume flow of gas or water and can be used to calculate the fee for the user. This application is good for gas or water meters. This application also includes the necessary information with regard to software and hardware procedures for the Water Meter Reference Design for two LC Sensors, Using Extended Scan Interface (ESI) ([TIDM-LC-WATERMTR](#)).

The software described in this app note can be downloaded from <http://www.ti.com/lit/zip/tidc583>.

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## Trademarks

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## 1 Introduction

The [TIDM-LC-WATERMTR](#) design uses the EVM430-FR6989 evaluation module and the MSP430FR6989 device to demonstrate the function of the Extended Scan Interface (ESI), which is designed for flow meters with a rotating disc to measure the flow rate. The ESI is good for LC, reed switch, GMR, and optical sensors. The MSP430FR6989 is an ultra-low-power MCU with up to 128KB of FRAM for code and data. Peripherals include RTC, ADC12, CRC, AES256, MPY32, eUSCI for communication, Comp\_E for touch key module, an LCD controller, and six timers. [Figure 1](#) shows a block diagram of the EVM, including all of the elements in the default EVM and potential add-on modules that can be added.

The main board of the EVM consists of an RF socket, a USB connection, and a dc-dc converter for the battery power. The RF module is turned off most of the time and is turned on only a few times per day for transmission of data. While the RF module is turned on, extra power is required. The dc-dc converter can output enough power to supply the module with high efficiency. All I/O ports are connected to a pack of through-holes on the PCB of the EVM. With these connections, the designer can add extra flow meter features like NFC/RFID for prepayment or a motor driver for valve control. A motor board is also provided to drive a rotor disc to emulate the rotating disc in flow meter. A sensor board with an LC sensor, GMR, or optical is also provided. In this application note, the LC sensors are used. The application code can be reused for other type of sensors.

### 1.1 System Block Diagram

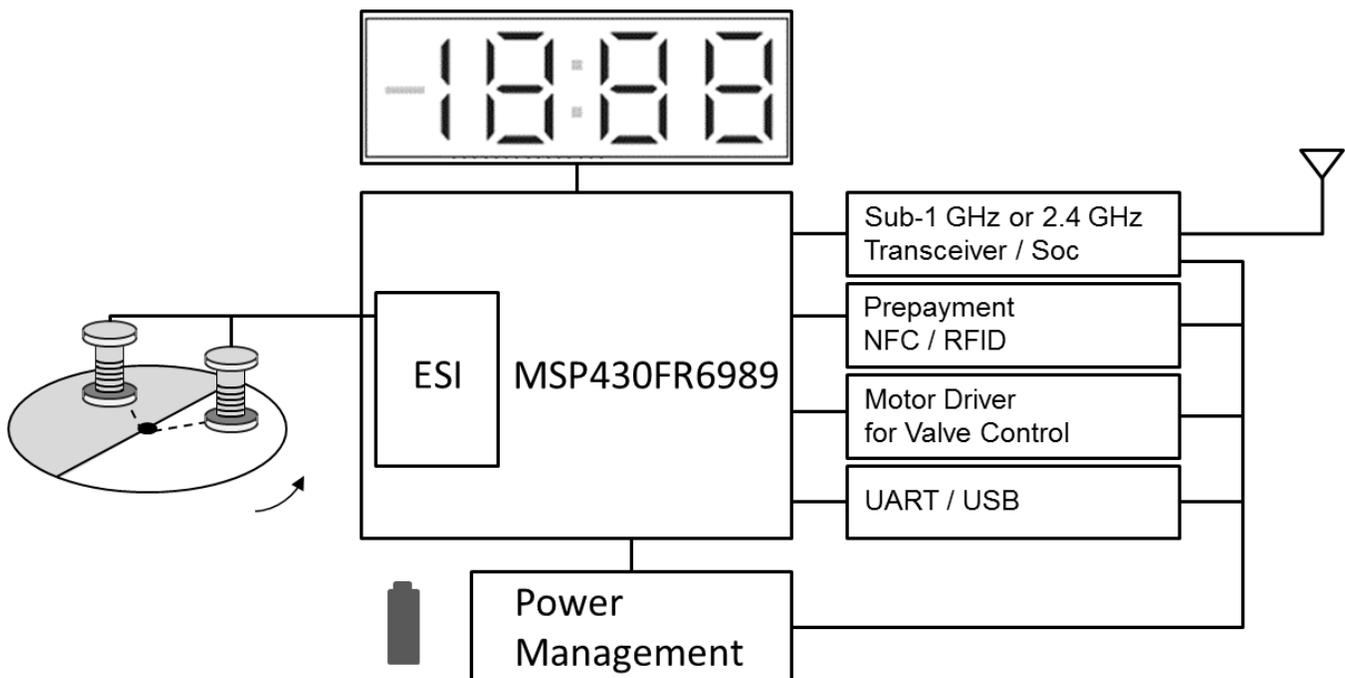
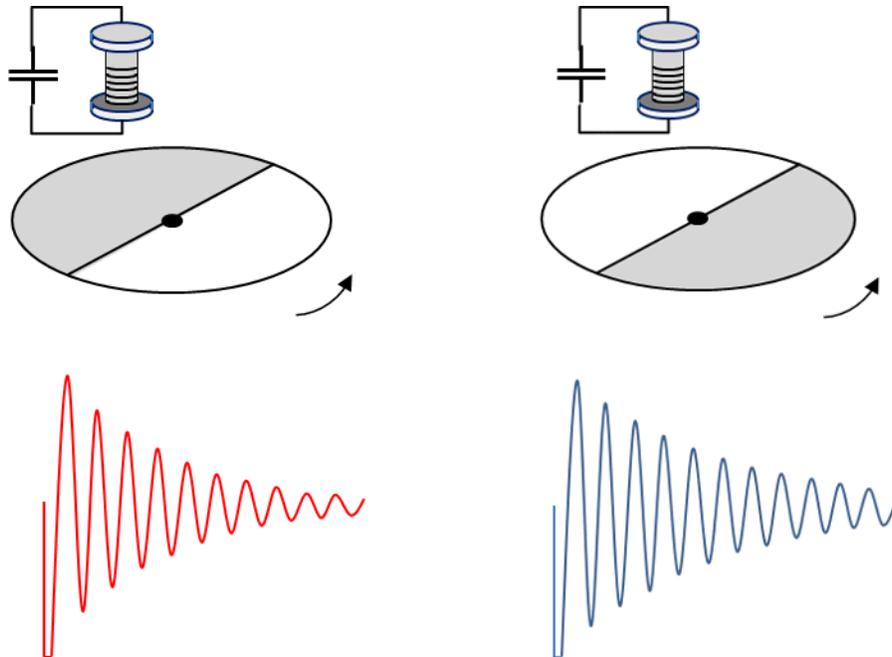


Figure 1. System Block Diagram

## 2 Working Principle of LC Sensors

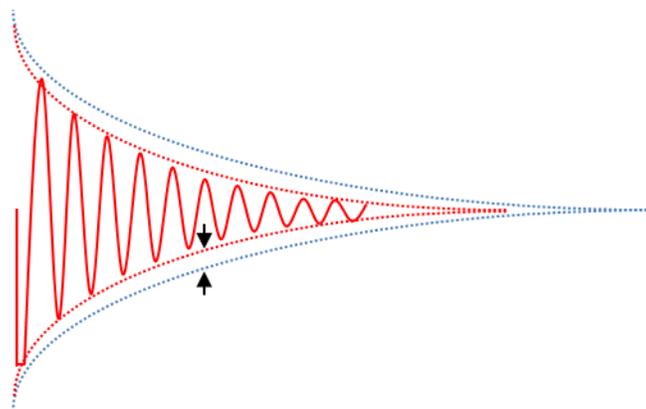
The LC sensor consists of an inductor and a capacitor. In the application circuit, 220 pF for the capacitor and 470  $\mu$ H for the inductor are used. After the capacitor is charged by a short pulse of period in 1  $\mu$ s, the LC sensor starts oscillating with a frequency of 500 kHz, and the signal voltage level decays. Varying with the inductor and capacitor used, the frequency and decay rate can be varied according to the ambient environment, like temperature and humidity. In this application note, room temperature is assumed.

When there is a metal approaching the oscillating LC, the signal decays faster due to the energy absorption by eddy current of the metal part. As shown in [Figure 2](#), by using this characteristic, the LC sensor is used to identify metal (signal in red) or nonmetal part (signal in blue). A disc that is half covered by metal and half by nonmetal can be constructed as a moving component to detect the flow rate. The rotation speed of the disc can then be detected by the LC sensor.



**Figure 2. Oscillation Signal of Detection of Metal And Nonmetal Portions of the Rotor Disc**

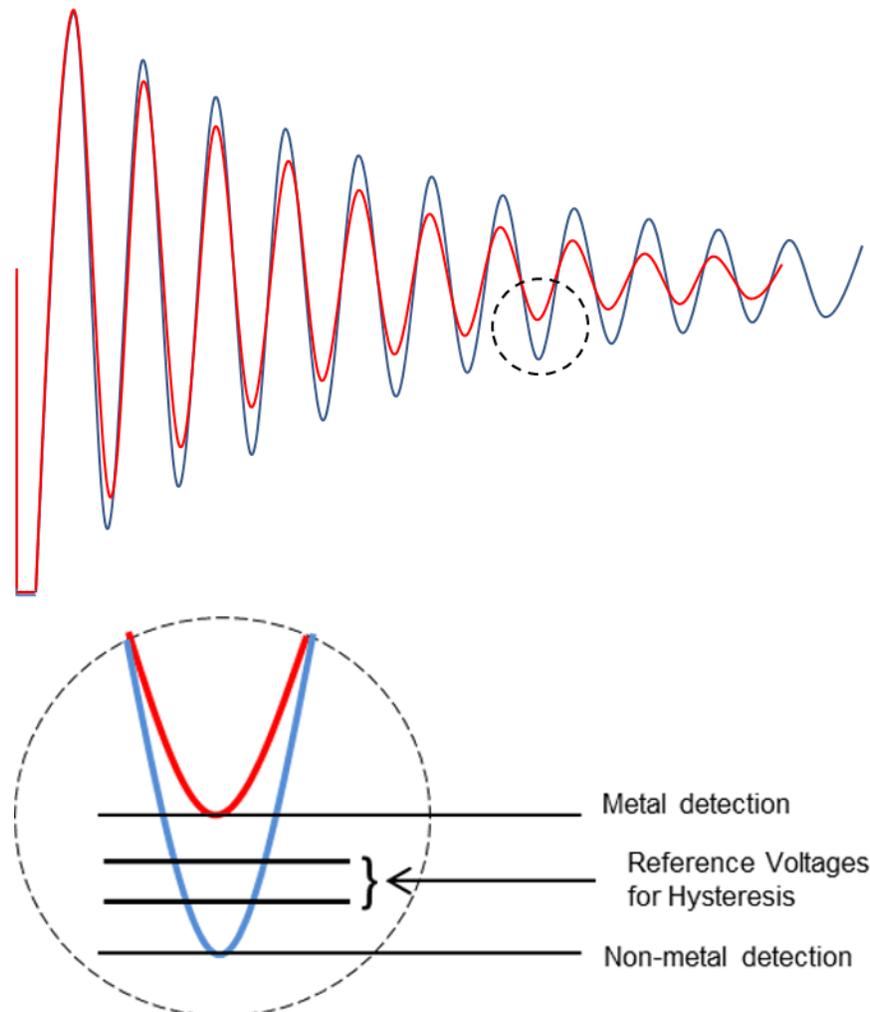
When overlapping these two oscillating signals of metal and nonmetal, the signal level difference of them is not constant. It starts from a small level to a largest difference in somewhere in the middle part of the signals and then decreasing to zero. For a maximum detection distance, only the portion of signals with maximum difference in signal level is measured (see [Figure 3](#)). This needs a timer to form a time delay before comparing these two signals.



**Figure 3. Maximum Difference Along the Decaying LC Signal**

To detect the metal and nonmetal signals, the EVM needs a reference signal with a voltage level be set in between the "red" and "blue" of the LC signals. In the ESI module, a DAC with 12-bit resolution is provided for this function. For analog hysteresis, two voltage references are provided from the DAC module of the ESI (see [Figure 4](#)). A comparator is then used to identify the metal and nonmetal parts of the disc.

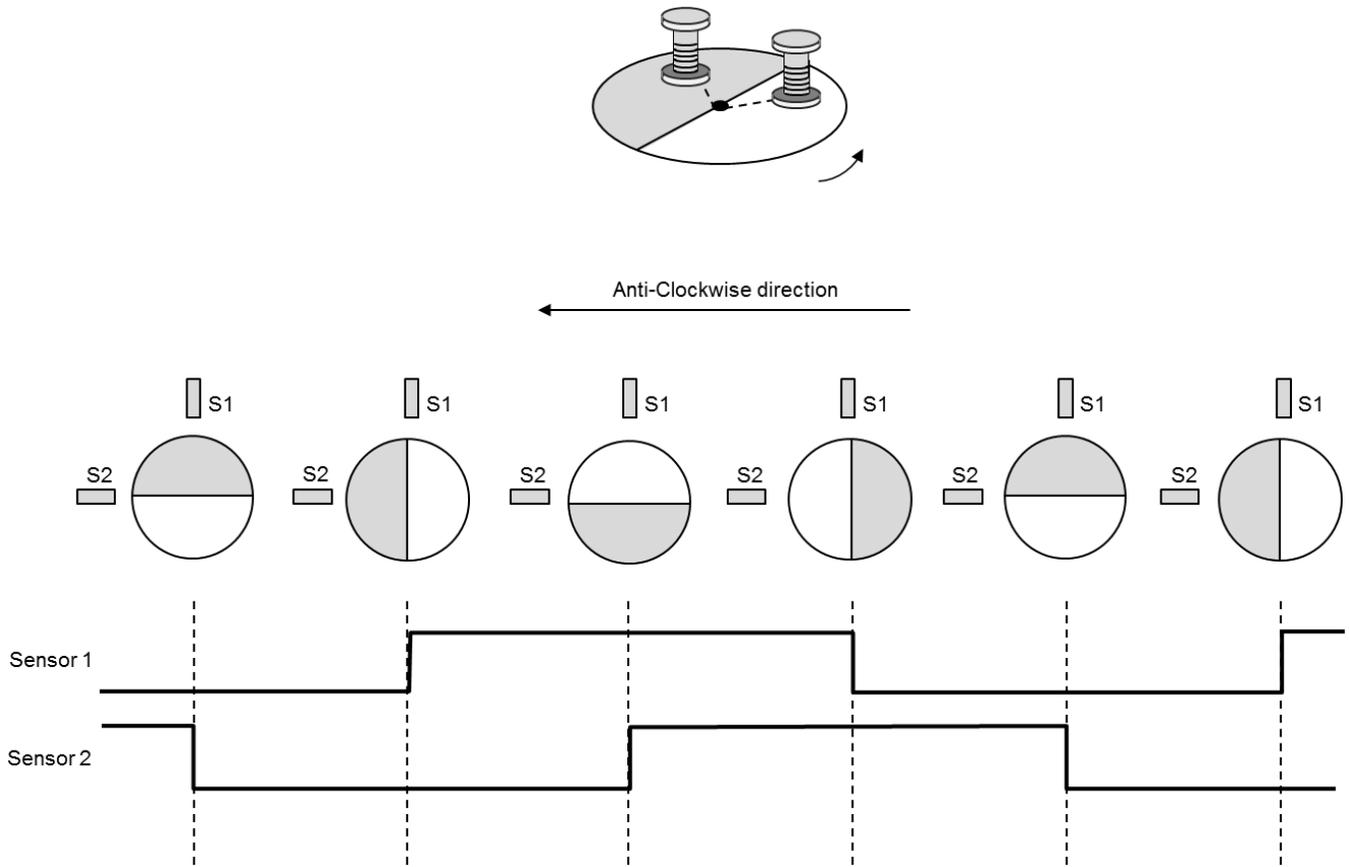
There are two possible positions to place the reference level, the upper range or the lower range of the LC signal. In the ESI, the operating voltage for the comparator is from  $V_{SS}$  to  $V_{CC} - 1$  V, and the operating voltage for the DAC is from  $V_{SS}$  to  $0.8 V_{CC}$ .  $V_{CC}$  is usually below 3.3 V. With these electrical characteristics, if the measurement uses the upper range of the oscillating signal, a time delay is needed to wait until the LC signal has decayed to below  $V_{CC} - 1$  V. However, when using the lower range of the signal, it can start functioning from  $V_{SS}$  up. This eliminates the need for a long delay in the beginning part of the signals. In this EVM, the lower range is used (see Figure 4). The signal level of a sensor is measured with the voltage level of the selected peak of its LC signal, which varies from metal to nonmetal.



**Figure 4. Reference Voltages for Detection of LC Signal to Identify Metal and Nonmetal Parts**

Two LC sensors are used for the detection of both clockwise and counterclockwise rotation. In a flow meter, such as a water meter, there is a bounce back of water flow when the tap is closed. This makes the rotor disc turn backward and forward repeatedly before the flow rate becomes zero. To eliminate the counting error with a single sensor, two sensors can count the number of rotations for both directions and give a correct result.

In Figure 5, a logic low is output when the sensor detects the metal part, and a logic high is output when the sensor detects the nonmetal part. The two sensors are located in  $90^\circ$  apart. Therefore, the signal of one sensor is always  $90^\circ$  out of phase to the other sensor. This configuration gives four states of the two sensors: 00, 01, 11, and 10. The sequence of these four states provides direction of rotation.



**Figure 5. Logical Signal Output of Comparator of ESI for Two Sensors**

### 3 Hardware Implementation With ESI

Figure 6 shows the block diagram of the ESI. There are three clock sources, ACLK of 32768 Hz, a built-in internal oscillator (ESIOSC) of ESI for a high-frequency clock source, and the SMCLK using the DCO. In the EVM, ACLK and ESIOSC are used.

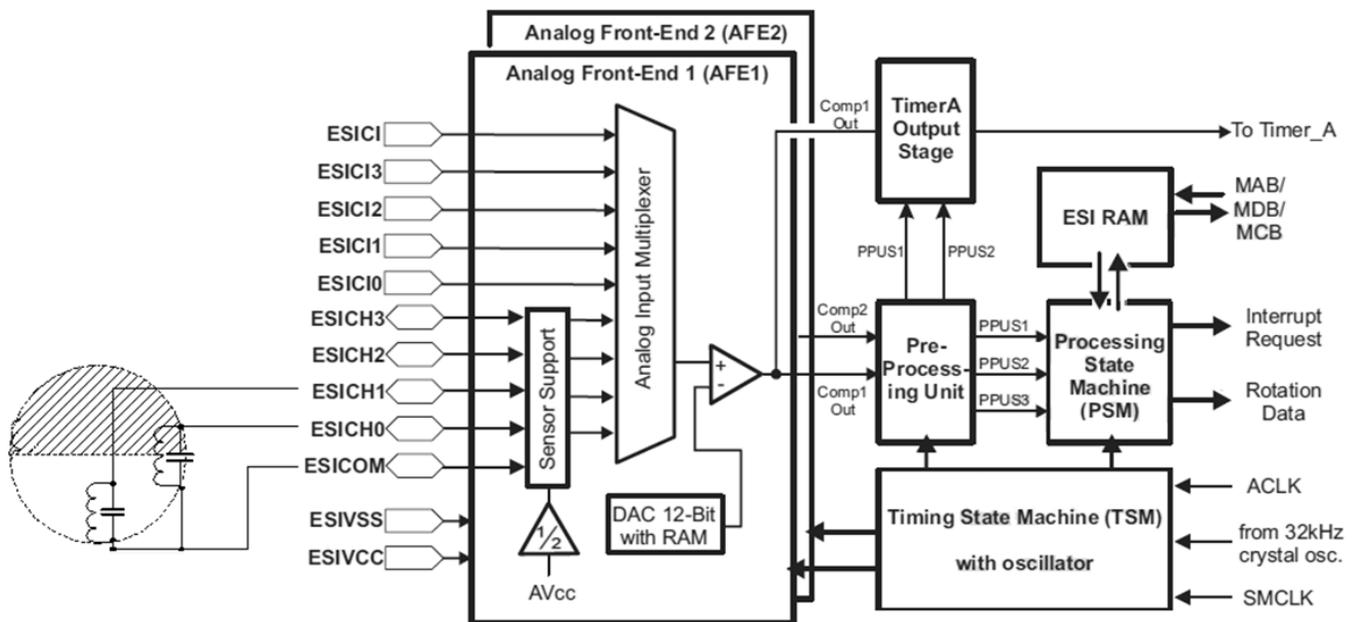


Figure 6. Block Diagram of the ESI

There are two analog front ends, AFE1 and AFE2. AFE1 provides  $V_{CC}/2$  as the ac ground of the LC signal and an excitation circuit to provide a short pulse in the range of microseconds for the excitation of LC oscillation. Up to four sensors can be connected to the four channels of the ESI. For each channel, the sensors are excited one by one.

The input signal of a sensor is connected to the positive input of a comparator. The negative input is connected to the 12-bit DAC. Two registers of the DAC for each channel provide two reference levels to implement hysteresis that avoids signal oscillation in the output of the comparator.

The 32 registers of the Timing State Machine (TSM) provide the timing sequence to control the on and off of the internal parts of the ESI module. The output of the comparator for each channel is stored in a register of the Preprocessing Unit (ESIPPU). After the completion of one cycle of measurement for all sensors (using two sensors in this EVM), an ESISTOP signal is generated to trigger the operation of Processing State Machine (PSM) to analysis the rotation direction and count the rotation number. The maximum number of processing channels is three out of four selectable channels. The channels are selected in ESIPPU, and their outputs are processed by PSM.

The AFE2 has DAC registers and a comparator. The inputs to the AFE2 share the same channels selection circuit of AFE1. With this configuration, the AFE2 measures the same signal that is being measured by AFE1. The outputs of AFE2 are stored in the ESIPPU. This design enables AFE2 to be the mirror of AFE1 and to perform a runtime recalibration of AFE1 without interfering with the normal operation of AFE1.

### 3.1 Rotor Plate and Detection Distance

The rotor plate or disc is used to detect the flow rate. This is a round disc that is half covered with metal and half covered with nonmetal. For a reasonable detection distance, the metal area cannot be too small, because a larger metal area has more absorption rate of the magnetic energy from the inductor of the LC sensor. The detection distance also relies on the concentration of the magnetic field from the inductor. When the disc is rotating, the LC sensor gives a large signal in the nonmetal part and a small signal in the metal part. The signal level is a continuous change from high to low and low to high. When the sensor is located in between the metal and nonmetal area, the signal is also between the maximum and minimum levels (see Figure 7).

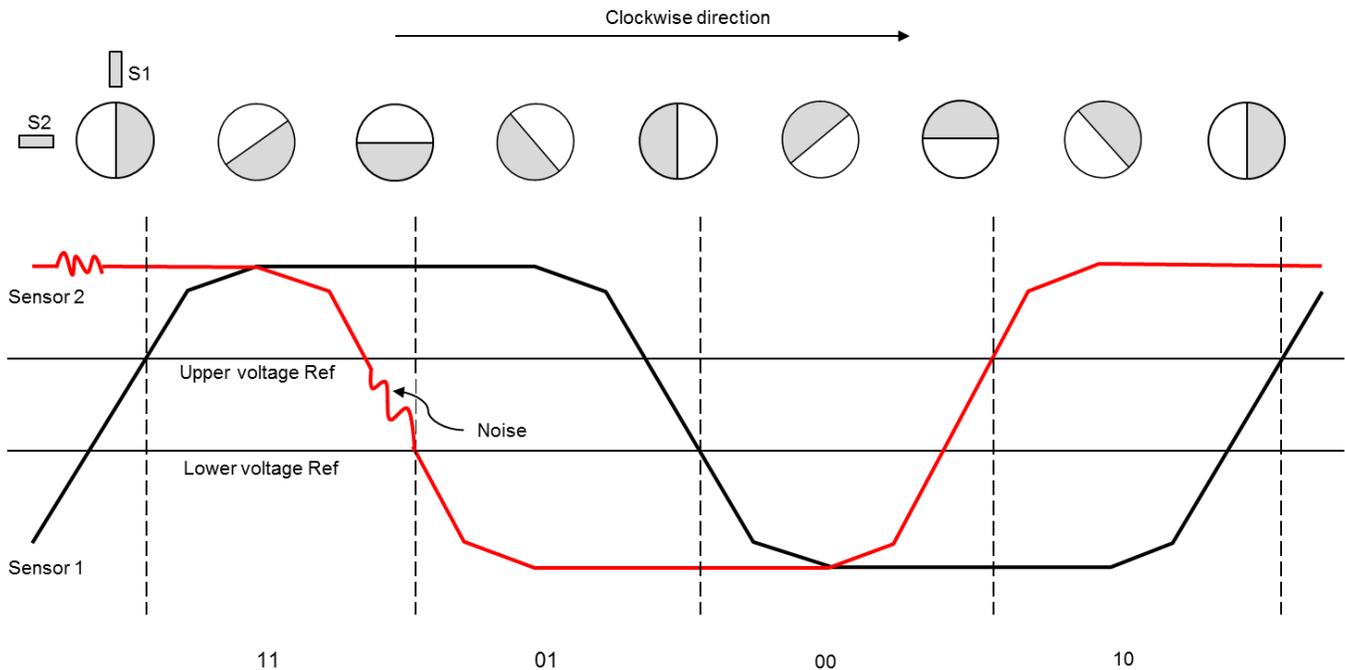


Figure 7. Signal Levels From Two Sensors

Each sensor signal has a 90° phase angle from the other. When the rotor disc rotates in clockwise direction, sensor 2 detects a high signal level when it is in the middle of nonmetal portion, and the signal level gradually decreases to a low level when detecting the middle of the metal portion.

There are two voltage references from DAC. When signal is in high level, the lower voltage reference is used, interpreting with logic high. As the rotor disc is rotating, the signal level changes from high to low, then low to high, and repeats continuously. A logic low results when the signal is lower than the lower reference. At the same time, the voltage reference is switched to the upper voltage reference to form analog hysteresis. It has logic high again only when the signal level is higher than the upper voltage reference. Similarly at this time, the voltage reference is switched to lower voltage reference.

Four states (11, 01, 00, and 10) are obtained, and each state occupies the same period of time. If the sensors are not placed 90° apart, some states have a shorter time period. This implies that a higher sampling rate is required to detect them, which increases power consumption.

The maximum detection distance is obtained with a large area of metal portion and an inductor designed to concentrate the magnetic field on to the metal area. Sensors have to output 90° phase angle. For a maximized solution, the rotor disc must be half covered with metal and half with nonmetal.

## 4 Software Implementation

Figure 8 shows a flowchart of the default software that is provided with the EVM.

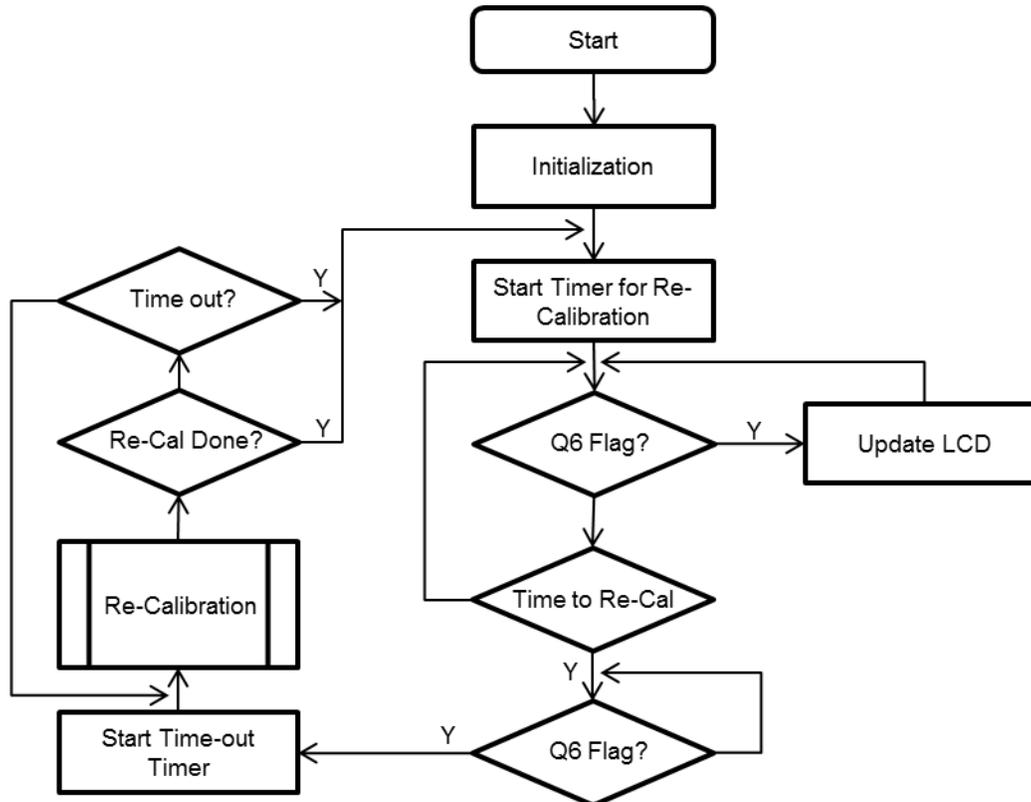


Figure 8. Flowchart of the EVM Software

### 4.1 Operation of Software

The software is optimized to reduce power consumption of the system (see Figure 8). It starts with initialization which includes ports setting for low current leakage, LCD, ESI internal oscillator calibration, ESI registers, sampling rate, timing state machine (TSM) with auto-TSM calibration, optimal DAC level, and processing state machine (PSM) table setting. After initialization, the EVM works well in low-power mode with the ESI and LCD as the only modules that are actively running.

To avoid too many interrupts to wake up the CPU, the Q6 flag in PSM table is used. This flag is set only when the rotor disc is rotating. The system is in LPM3 mode when there is no rotation. To further lower the power consumption, the designer can disable the LCD and add a key button to wake up the LCD when reading is necessary.

For stable operation throughout the life time of the system, runtime recalibration for tracking the drift of the sensors and system is provided. A timer with variable constant "Time\_to\_Recal" is used to count the period for recalibration. The software is design to operate two sensors. For easy description in this document, only the first channel or channel 0 is mentioned. The second channel works in a similar way.

### 4.2 Initialization

#### Port and LCD setting for low-power operation

To enable low power consumption during ESI operation, the CPU wakes only on interrupts. In normal state, the rotor disc is not rotating and no interrupt is generated. Q6 of the PSM in normal running mode and the ESISTOP flag during runtime recalibration mode are the only interrupt flags that wake the CPU.

All ports must be set to minimize low leakage. Unused pins should all be set to output zero.

Port 1.2 is used as ADC input for the key pad. This port pin is set to be input mode with the pullup resistor enabled.

For Port 9 pins that are multiplexed with ESICH0 to ESICH3, all P9SEL0 and P9SEL1 register bits must be set to 1 for the operation of the ESI function, even when working with two channels. At the same time, the peripheral comparator has pins multiplexed with ESI. The port disable register must be set to prevent parasitic current during the transition level of the gates in the port pins. To disable the port, CECTL3 must be set to 1.

In the application code, the LCD is always on. To further lower the power consumption, it is suggested to turn the LCD off and to turn it only for reading.

### 4.3 ESI Internal Oscillator Calibration

There are three clock sources associated with the ESI: ACLK, SMCLK, and the internal oscillator of ESI. The internal oscillator and the SMCLK are the sources of high-frequency clocks which could be used in the TSM timing control. For low power and standalone operation of ESI, the internal oscillator is preferred. However, this clock frequency varies from device to device, so an initial calibration is required. The calibration code can be found in ESI\_ESIOSC.c.

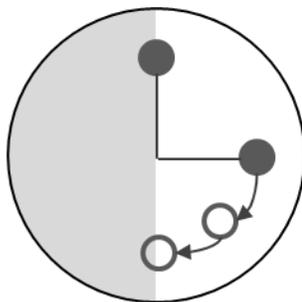
### 4.4 Sensor Sampling Rate Setting

For normal operation, the sampling rate of ESI is the frequency of triggering a LC oscillation so as to detect the position of the sensors over the rotating disc. The register used is ESITSM. The equation to determine the rate is as follows:

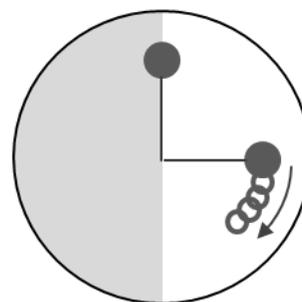
$$\text{Sampling Rate} = \text{Maximum Rotation Rate} \times \text{Number of Samples per Rotation}$$

$$\text{Number of Samples per Rotation} = 2 \times 360 / (\text{Angle of smaller portion of the Disc} - \text{Angle of sensor pair})$$

In the half metal, half nonmetal rotating disc, the angle of smaller portion is 180°. The angle of sensor pair is 90°. The detection area is then the difference between these number which is 90°. There are two samples in this area to make sure it is detected (see Figure 9a). For one complete rotation, the number of samples are determined. The sampling rate is found by multiplying this number by the maximum rotation rate. Therefore, if a maximum rotation rate is 50 rotations per second, the required sampling rate is 400 Hz. In the code of reference design, 500 Hz is used.



a) Sampling rate in normal run



b) Sampling rate in runtime recalibration

**Figure 9. Sampling Rates**

For runtime recalibration to determine the signal level of sensors, a faster sampling rate is required to enable the recalibration algorithm to be completed within a certain period of time. For example, a recalibration process is triggered when a sensor reaches the middle part of nonmetal area. For a maximum rotation rate of 50 per second, sampling rate of 2000 is required to complete the process with 5 samples in one eighth of a rotation (see Figure 9b). In the reference code, 2340 Hz is used. The equation is as follows:

$$\text{Sampling Rate} = \text{Number of Samples} / \text{Time for recalibration}$$

$$\text{Time for recalibration} = 1 / \text{Maximum Rotation Rate} / 8$$

## 4.5 Auto-TSM Calibration

The Timing State Machine (TSM) is to control the timing of each state and the registers used are ESITSMx. Referring to the user guide, the 5 most significant bits of the register are to determine the period of time for the corresponding state to last for. Afterwards, the TSM jumps to the next state. Repeating this process until the ESISTOP bit is set to complete one TSM cycle. An ESISTOP flag is generated and the TSM is repeated after waiting for a time interval of one sampling period. (An auto repeating setting is used in this reference code. However the TSM can be set to be restarted by software control).

The following is the initial setting of TSM registers.

```

ESITSM0 = 0x0400; // DAC=off, CA=off, 1xACLK
ESITSM1 = 0x202C; // DAC=off, CA=off, 5xESICLK, excitation
ESITSM2 = 0x0404; // DAC=off, CA=off, 1xACLK
ESITSM3 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM4 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM5 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM6 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM7 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM8 = 0x0024; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM9 = 0xF134; // DAC=on, CA=on, 31xESIFCLK,
ESITSM10 = 0x5974; // DAC=on, CA=on, OUTPUT LATCHES ENABLED, 12xESICLK
ESITSM11 = 0x0400; // DAC=off, CA=off, 1xACLCK, internally damped
ESITSM12 = 0x0400; // DAC=off, CA=off, 1xACLCK, internally damped
ESITSM13 = 0x20AD; // DAC=off, CA=off, 5xESICLK, excitation
ESITSM14 = 0x0485; // DAC=off, CA=off, 1xACLK
ESITSM15 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM16 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM17 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM18 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM19 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM20 = 0x00A5; // DAC=off, CA=off, 1xESIFCLK, delay tunable
ESITSM21 = 0xF1B5; // DAC=on, CA=on, 31xESIFCLK
ESITSM22 = 0x59F5; // DAC=on, CA=on, OUTPUT LATCHES ENABLED, 12xESICLK
ESITSM23 = 0x0200; // stop
  
```

The corresponding LC signal of channel 0 is shown in [Figure 10](#).

At **point 1**, the TSM starts with ESITSM0 of 0x0400 which is the beginning state of TSM cycle. This state is to synchronize with the rising edge of ACLK. This ensures the following timing of states to be the same for every TSM cycles.

At **point 2**, ESITSM1 is to make an excitation pulse for the channel 0 with timing last for 5 clock of ESI internal oscillation. The length of the pulse must be long enough to ensure the first shot of oscillation to reach the voltage of  $V_{CC} + V_{diode}$  ( an internal protection diode of I/O). This makes every oscillation identical.

At **point 3**, the LC sensor starts oscillating and its signal amplitude is getting smaller. ESITSM2 last for 1 ACLK. An additional delay with high frequency clock from ESI oscillator is turned on to fine tune the delay time and last for a period which is the sum of the time delay from ESITSM3 to ESITSM8. By using ESITSM2 to ESITSM8, an auto TSM time delay function "TSM\_Auto\_cal()" is constructed to tune the time delay of the LC signal, so as to reach an optimal signal level and timing to capture a signal ( in point 5). This function is to add on one high frequency clock cycle delay every time. The captured signal is then measured by a function "FindDAC()" to find its voltage level, by using the comparator and the DAC as reference voltage. With this setting, only the peak level is measured. In the reference design, an inverter is enabled to invert the output of comparator so that the crisis of LC signal is measured. If plotting the value of the measured level into a graph, an envelope of the signal with a stair-case-shaped curve is obtained. when the signal level has reached the pre-defined level "LC\_Threshold\_TSM\_CAL", an optimal delay is obtained at a point which is the mid-way to the next crisis.

At **point 4**, ESITSM9 is to turn on the comparator and DAC output. A proper delay is taken for the settling time.

At **point 5**, ESITSM10 is to latch in the output of comparator and stored in ESIPPU. One of function of high frequency clock delay from ESITSM3 to ESITSM8 is to select a mid-point between two peaks or two crisis for triggering the latch in function. The selection of mid-point provides the maximum margin of phase noise to detect the peak of the LC signal.

At **point 6**, ESITSM11 and ESITSM12 switch off the comparator and DAC. They also provide two ACLK of time for internal damping of the LC sensor of channel 0, by shorting the sensor. This makes sure that it does not keep oscillating and induce crosstalk noise to the next channel.

From ESITSM13 to ESITSM22 is repeating the same process for channel 1. ESITSM23 generates a stop signal to complete the TSM cycle.

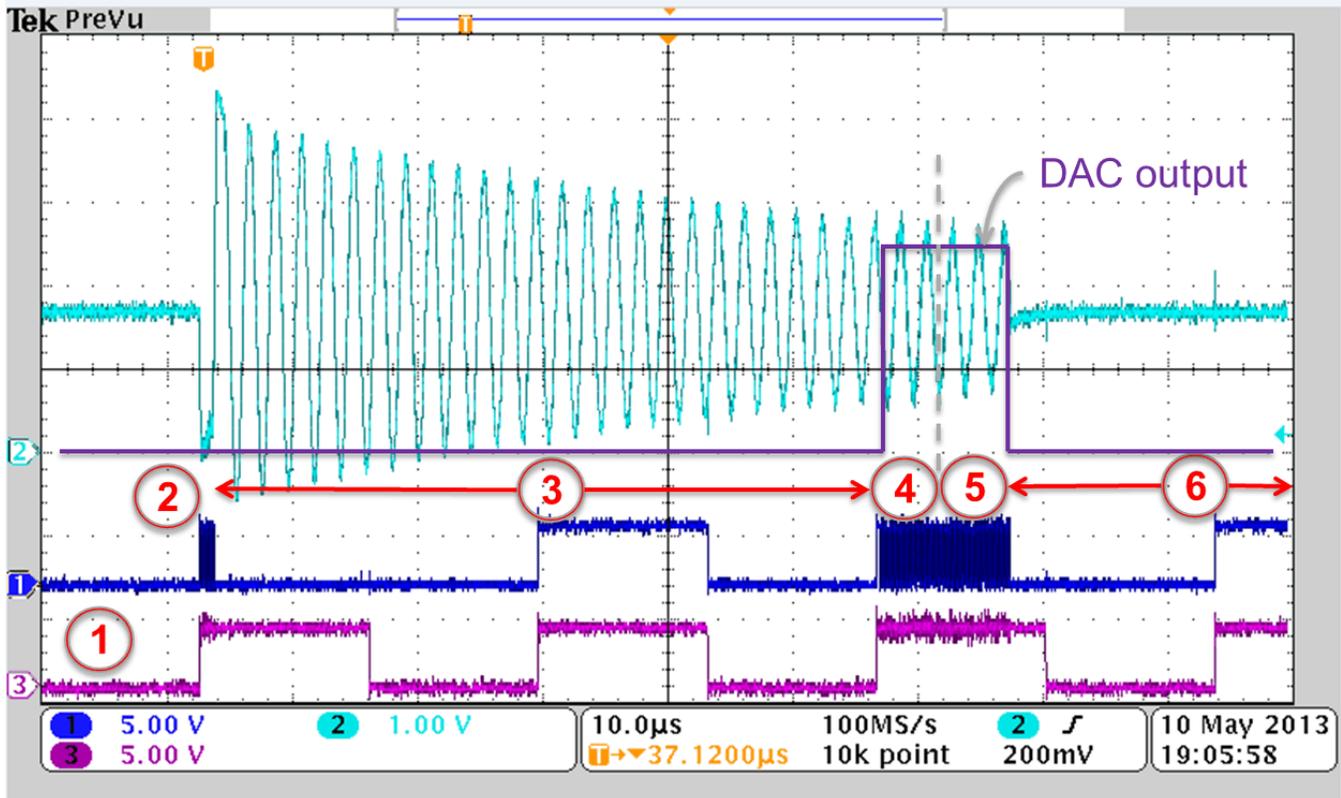
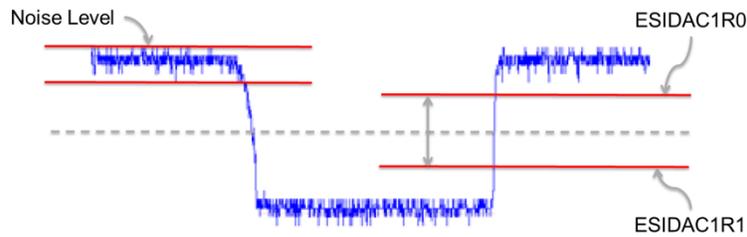


Figure 10. Different States Along an LC Signal

#### 4.6 Optimal DAC Voltage Level Setting

The DAC in the ESI generates a reference voltage for the comparator. To eliminate or reduce the oscillation when the voltage of input signal is close to voltage reference of DAC, two DAC registers "ESIDA1R0" and "ESIDAC1R1" are used to provide two reference voltage for analog hysteresis. This is especially important when the sensor is on the border line of metal and nonmetal part of the rotor disc. The issue is how large should it be for the separation of these two levels. If the separation is small, oscillation may frequently occur. If it is too large, it increases the voltage difference required between the maximum and minimum of sensor signals and, in turn, reduces the detection distance.

Noise level of signal is then a significant data for the optimal setting of analog hysteresis. With a closer look to the sensor signal (see Figure 11) there is a small noise when the sensor is located onto either the metal or nonmetal part of the disc. This noise can be measured wherever the signal level is. As noise amplitude is within the "Noise Level", seldom exceeding it, the optimal hysteresis setting can then be set as the mid-level between the maximum and minimum of signal plus and minus the noise level.



ESIDAC1R1 = (Max\_DAC\_Ch0 + Min\_DAC\_Ch0)/2 + Noise\_level; // "+" for INV version, "-" for nonINV version

ESIDAC1R0 = (Max\_DAC\_Ch0 + Min\_DAC\_Ch0)/2 - Noise\_level; // "-" for INV version, "+" for nonINV version

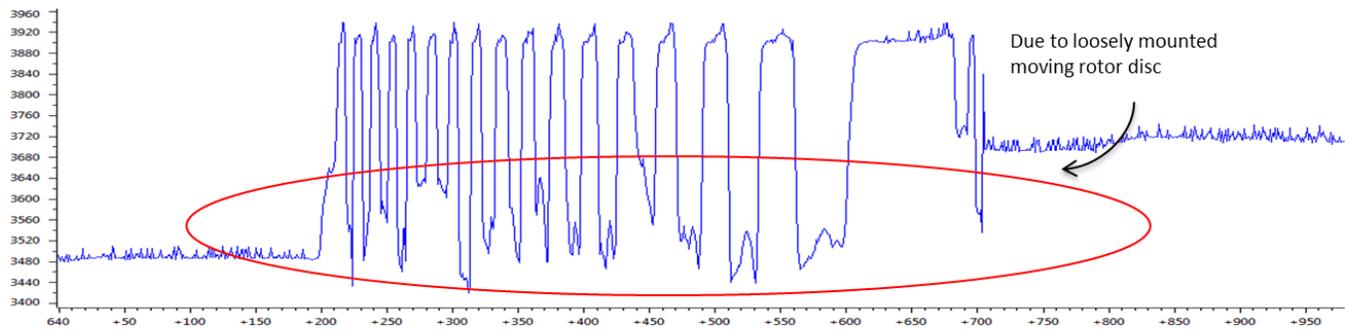
**Figure 11. Noise Level of Signal Determines Values of Two Reference Voltages of DAC**

The noise level is measured when the rotor disc is not turning. The function "Find\_Noise\_level()" is responsible for this measurement, in which "FindDAC\_Fast\_Range()" is the algorithm to search for the signal level. This function is to measure the variation of signal for 0.5 second with the sensors staying at the same position over the disc. The noise level is then the difference between the maximum and minimum of the measured data.

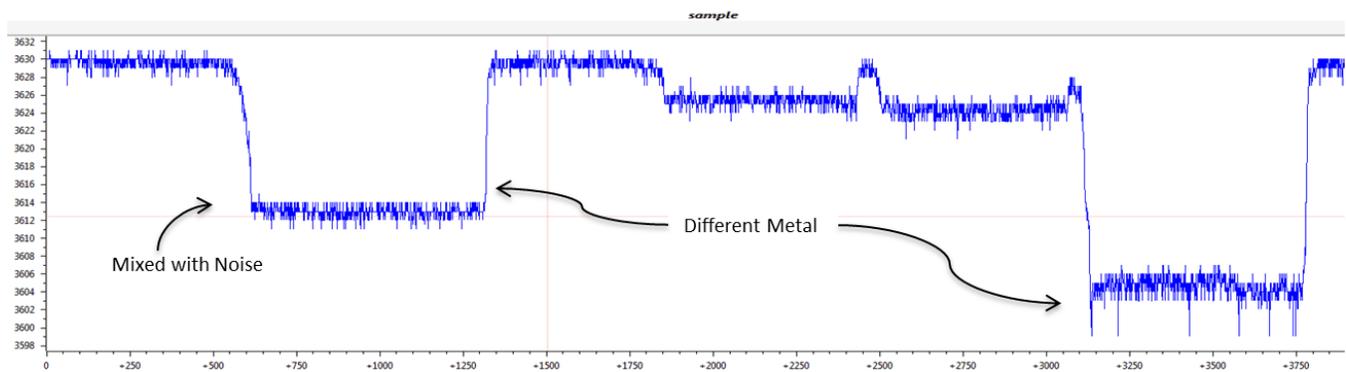
The Max\_DAC\_Ch0 and Min\_DAC\_Ch0 of channel 0 are respectively the maximum and minimum value of the sensor signal with the rotor disc rotating. To measure these two data, in the function "Set\_DAC()", the rotor must be rotating for 1 second, making sure the metal and nonmetal part of the disc are measured. The channel 1 is also going through the process at the same time.

To ensure the data correctly measured, the axis of rotor disc must be mounted tightly and in a perpendicular position in reference to the sensors. If it is loosely mounted, the minimum of the signal varies because of the varying distance between the sensors and the metal part of the disc. For nonmetal part, there is no such variation (see [Figure 12a](#)).

To increase the difference between the maximum and minimum of the signal, a metal with higher energy absorption rate can work. From the testing, stainless steel has better absorption rate than copper, while copper is better than aluminum (see [Figure 12b](#)).



a) Signal of detection of metal portion of a loosely mounted rotor disc



b) Signal level of different metals

Figure 12. Signal Levels

#### 4.7 Processing State Machine (PSM)

The function of PSM is to process the input from ESIPPU so as to detect the position of the sensors on the rotor disc and then increase or decrease the rotation counters ESICNT0, ESICNT1 and ESICNT2 when the rotor disc is rotating. ESICNT0 is to record the number of rotation when the rotor disc is rotating in clockwise direction, in parallel to the direction of water flow, while the ESICNT2 is for anti-clockwise rotation. ESICNT1 is the resultant number of rotations, which records the data equivalent to  $ESICNT0 - ESICNT2$ . Interrupt flags can be set on Q6 and Q7 of the PSM vector. There are some other interrupt settings with the outputs of the counters. The family user's guide ([SLAU367](#)) explains them in more detail. In this application code, only the Q6 of PSM vector is used for the interrupt call.

There are two channels, Ch0 and Ch1. The sensors for these channels report their detection in a timely manner according to the sampling rate. When the rotor disc is rotating, there generates four inputs namely: 00, 01, 11 and 10 (see [Figure 13](#)). At the same time, the position of sensors over the rotor disc can be determined. Four states are used to represent the location of the sensors, namely: S0, S1, S2, and S3, with S0 indicating both sensors are on metal part; S1 for Ch0 on nonmetal and Ch1 on metal; S2 for both sensors on nonmetal part; and S3 for Ch0 on metal and Ch1 on nonmetal part. The direction of rotation can then be found by processing the sequence of the states.

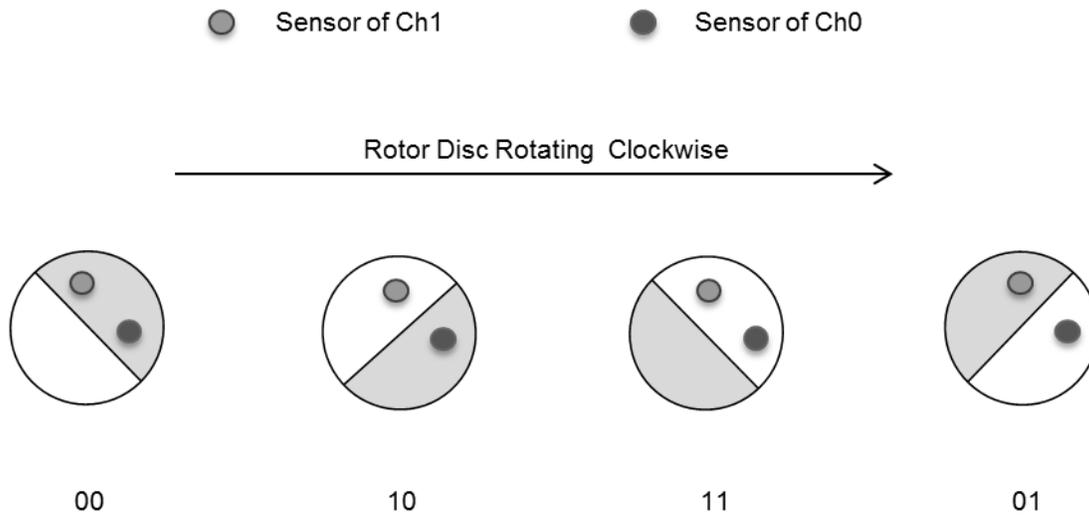


Figure 13. Different States of LC Sensors When Rotor is Rotating

#### 4.7.1 State Diagram

A state diagram can then be used to clearly show the flow of the states (see Figure 14) with different inputs and outputs. At the starting of the ESI module, the sensors are located at one of the four positions over the rotor disc and a state is given. If the disc is not rotating, there the sensor input does not change and the same state is kept. The output is 0. For this description, assume that the initial state is S0. The nonrotating disc makes the sensors have 00 as input to the PSM. The state is kept in S0 and the output is 0.

When the rotor is rotating clockwise, the state diagram flows from S0 to S1, S1 to S2, S2 to S3, S3 to S0, with inputs of 01, 11, 10, and 00, respectively, and continuously repeats this sequence as it keeps rotating. At the same time, the state diagram also outputs 1 when there is a state change. This increases the counters ESICNT0 and ESICNT1 by 4 for a complete clockwise rotation.

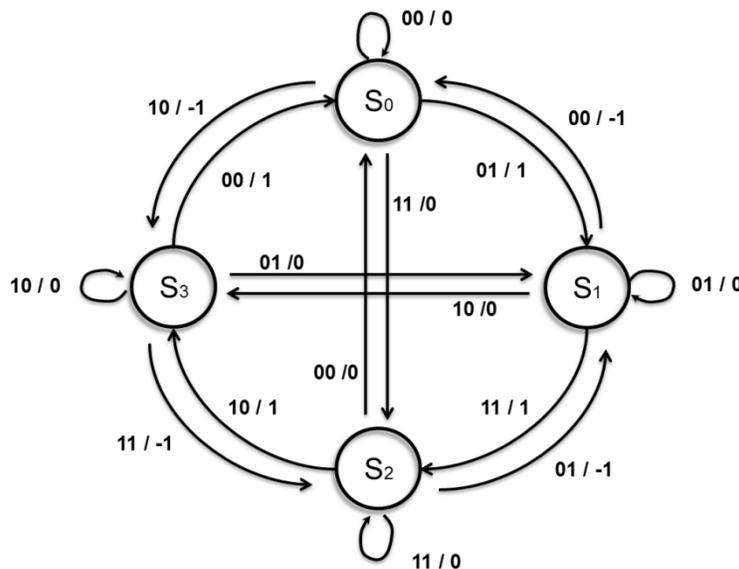


Figure 14. State Diagram of Two Sensors

When the rotor disc is rotating in an anti-clockwise direction, the state diagram flows in the other direction, from S0 to S3, S3 to S2, S2 to S1, S1 to S0, with inputs of 00, 11, 01, and 10, respectively, and continues to repeat this sequence when it keeps rotating. The output is -1 for each change of state, which decreases the counts ESICNT1 and ESICNT2 by 4 for a complete anti-clockwise rotation.

This state diagram includes a feature to adjust to vibration of the rotor disc. Assuming that the disc is rotating in clockwise when water is flowing, the counter increases in this direction. However, there is a bouncing back of water when the tap is closed. A backward flow causes the rotor to rotate in an opposite direction, and the state diagram reduces the counters accordingly. In the critical moment when the water is flowing forth and backwards rapidly, the counters have to count up and down without missing a single count.

The state diagram also provides a state change when there is an error input, for example, from S0 to S2 or S1 to S3. This can happen when the rotation speed is too high for the sample rate or when there is an error from the sensor input. To eliminate the error input, the sampling rate must be set high enough in reference to the maximum rotation speed. In addition, proper noise level and DAC level settings are required. If there has error input from a sensor, the error state simply outputs 0, which does not affect the counter, and quickly returns to the normal state. The worst case would miss two counts if it does not go back to the previous state. In this application code, there is no extra error handling for this type of error. However, Q7 of the PSM table is defined for generating an interrupt flag for this error. If designers need to build a dedicated error handling code, an interrupt is needed. Designers have to enable the interrupt enable bit for their interrupt coding.

#### 4.7.2 State Diagram to State Table

To convert the state diagram into a PSM table (see [Table 1](#)), S0 to S3 must be given a code. Put S0 = 00, S1 = 01, S2 = 11, and S3 = 10. In the PSM table, Q0 to Q7 represent the bit number of the register. The next state is represented by Q3 and Q0; the output is set by Q1 and Q2. When Q1 is set, the ESICNT0 and ESICNT1 are increased by 1. When Q2 is set, the ESICNT1 is decreased by 1 and ESICNT2 is increased by 1. Q7 is set when there is an error input, indicated with red highlight in [Table 1](#). Q6 is set when there is a state change in a clockwise direction, indicating with blue highlight in [Table 1](#). Q4 and Q5 are not used in the application code.

The Q6 is another interrupt flag of PSM table. In the application code, when Q6 is set, it triggers an interrupt code to update the LCD display. This is a design for low power consumption for CPU being in idle mode when the rotor disc is not rotating.

**Table 1. State Table Converted From State Diagram**

Present State of ESI		Input		Output		Next State		Interrupt to have	
		Ch1	Ch0	Q2 (-1)	Q1 (+1)	Q3	Q0	Q7	Q6
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	1	0	1	0	1
0	0	1	0	1	0	1	0	0	0
0	0	1	1	0	0	1	1	1	0
0	1	0	0	1	0	0	0	0	0
0	1	0	1	0	0	0	1	0	0
0	1	1	0	0	0	1	0	1	0
0	1	1	1	0	1	1	1	0	1
1	0	0	0	0	1	0	0	0	1
1	0	0	1	0	0	0	1	1	0
1	0	1	0	0	0	1	0	0	0
1	0	1	1	1	0	1	1	0	0
1	1	0	0	0	0	0	0	1	0
1	1	0	1	1	0	0	1	0	0
1	1	1	0	0	1	1	0	0	1
1	1	1	1	0	0	1	1	0	0

By rearranging the bit order in [Table 1](#), the PSM table is formed as [Table 2](#).

The Hex values are then put into the code and stored in the RAM of PSM.

**Table 2. PSM Table by Rearrangement of Bit Order of the State Table**

Error Flag	Rotation Flag	Rearrangement of Bit Order						Hex Value
		Q5	Q4	Q3	Q2	Q1	Q0	
0	0	0	0	0	0	0	0	0x00
0	1	0	0	0	0	1	1	0x43
0	0	0	0	1	1	0	0	0x0C
1	0	0	0	1	0	0	1	0x89
0	0	0	0	0	1	0	0	0x04
0	0	0	0	0	0	0	1	0x01
1	0	0	0	1	0	0	0	0x88
0	1	0	0	1	0	1	1	0x4B
0	1	0	0	0	0	1	0	0x42
1	0	0	0	0	0	0	1	0x81
0	0	0	0	1	0	0	0	0x08
0	0	0	0	1	1	0	1	0x0D
1	0	0	0	0	0	0	0	0x80
0	0	0	0	0	1	0	1	0x05
0	1	0	0	1	0	1	0	0x4A
0	0	0	0	1	0	0	1	0x09

## 5 Runtime Calibration With AFE2

When a flow meter is installed, it is expected to run for many years until the battery is drained. Due to environmental variation and component decay, the sensor signals will drift. To follow this signal drift, the reference voltages from DAC have to follow. This process requires a runtime recalibration of the system (see Figure 15). At each recalibration, the system is still working well and needs only a small calibration to follow a small drift. With this operation, even there is a large up or down drift over a long time, this runtime calibration keeps the DAC reference voltage at the optimal level.

As the system is battery powered, power consumption is a concern. In the ESI module, there has an extra analog front end (AFE2) with duplicated DAC and comparator, connecting to the common sensors of AFE1. When processing the calibration, AFE2 is switched on to measure the same signals that AFE1 is detecting. No extra excitation of a dummy signal is required. This cuts half of the power consumption that is required by the Scan Interface (SIF) in the MSP430FW42x series.

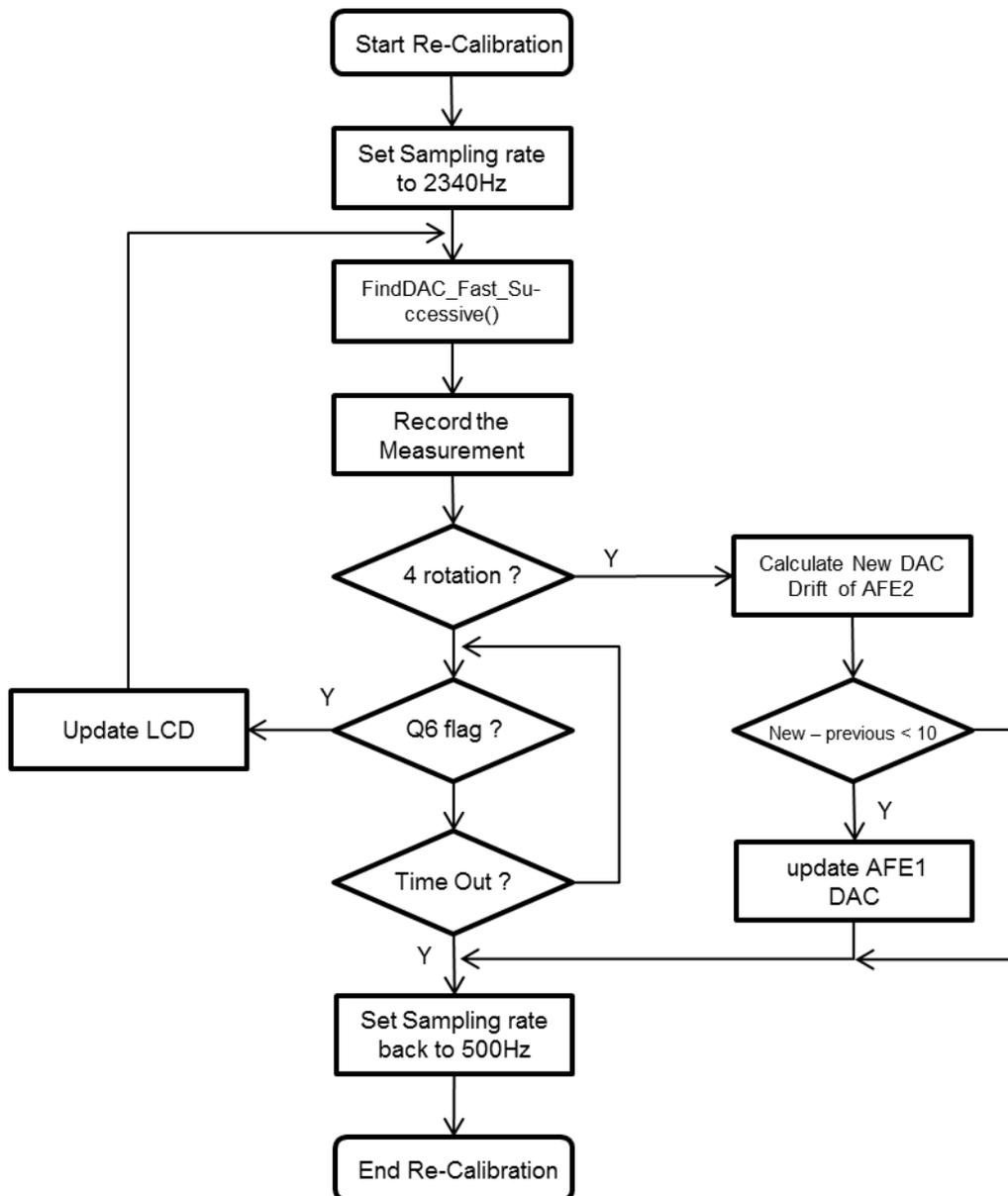


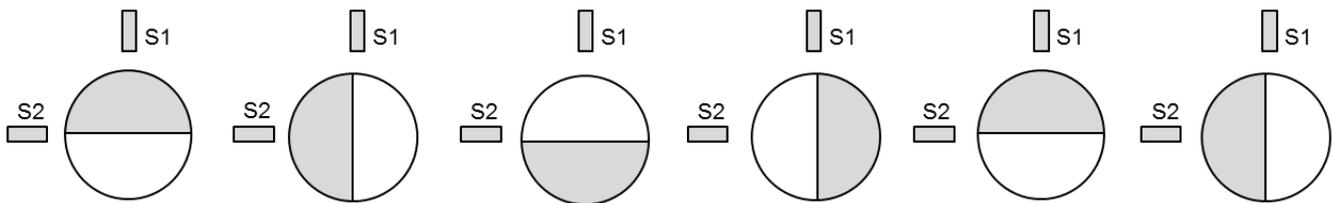
Figure 15. Flowchart of Runtime Recalibration

### 5.1 Operation of Recalibration

During the normal operation, there is a timer to activate the recalibration process. The timer interval should be set within a period during which a small drift expected. The designer can modify the constant "Time\_to\_Recal" to change the timing. The input clock for the timer is 32768 Hz.

When the process is activated, the MCU is in LPM3 mode until an interrupt is triggered by the Q6 flag from the PSM connected to AFE1. During recalibration, AFE1 continues normal operation, and AFE2 is turned on for signal level measurement. The Q6 flag is set only when the rotor disc is rotating in clockwise direction and there is a change of state of a sensor. This ensures low-power operation during recalibration. See the flow chart of runtime recalibration in [Figure 15](#).

As the two sensors are located in 90° apart, one sensor must be located at the center of the metal or nonmetal area of the rotor disc when the other sensor detects a change of state by AFE1 (see [Figure 16](#)). Using this property, the signal level of this sensor is always the maximum or minimum. As this is measured with the rotor disc rotating, the measurement algorithm is required to be fast and time deterministic. By using the function AFE2\_FindDAC\_Fast\_Successive() for AFE2, the signal level can be measured in five measuring cycles. A faster sampling rate of 2340 Hz is required to make sure that the sensor under measurement is kept on the same side of the disc and the signal level remains in a constant level. For sampling rate setting, see the section of sampling rate.



**Figure 16. Transition States Of A Sensor**

Because AFE1 and AFE2 are both inside the single MCU, the environment is identical to both of them. When there is a drift in AFE2, there is a similar drift in AFE1. Therefore, when a drift is determined in AFE2, the new level of AFE1 can be added with the same level of drift.

After four complete rotations, the recorded measurements are used to calculate the drift of AFE2 and the new DAC level of AFE1, as follows for channel 0. similar for channel 1.

$$\text{AFE2\_drift0} = (\text{AFE2\_Max\_DAC\_Ch0} + \text{AFE2\_Min\_DAC\_Ch0})/2 - \text{AFE2\_base0};$$

$$\text{New\_level} = \text{AFE1\_base0} + \text{AFE2\_drift0};$$

$$\text{Delta} = (\text{ESIDAC1R0} + \text{ESIDAC1R1})/2 - \text{New\_level};$$

If "Delta", the difference between the new level and previous level of DAC of AFE1, is less than 10, a valid measurement is confirmed and the new DAC values are set for channel 0 of AFE1, as calculated in these equations.

The designer can modify the condition value for a validation of measurement, but it cannot be larger than the half of the normal separation of maximum and minimum. If the condition exceeds this value, it can be treated as noise, because the ESI is still working during recalibration, and expects a small drift.

$$\text{ESIDAC1R0} = \text{New\_level} - \text{Noise\_level};$$

$$\text{ESIDAC1R1} = \text{New\_level} + \text{Noise\_level};$$

After that, the recalibration is finished. The sampling rate is changed back to normal rate and the timer restarts for the next calibration. There is a timeout timer of two seconds during the recalibration process. If the rotor does not move for two seconds, the process times out, the sampling rate is changed back to the normal rate, and the application waits for the next calibration.

## 6 Demo and Operation

### 6.1 Main Board

The main board of the EVM uses the MSP430FR6989 device with an LCD display (see [Figure 17](#)). This board is powered by USB and provides 3.3 V  $V_{CC}$  through a buck converter. It can be divided into seven parts, which are shown in [Table 3](#) and described in [Table 3](#).

This board is a platform for the development of a flow meter with RF and USB connection. The application software includes code for the ESI module for flow measurement. The default software does not have code for connection to Part 1, Part 5, and Part 6.

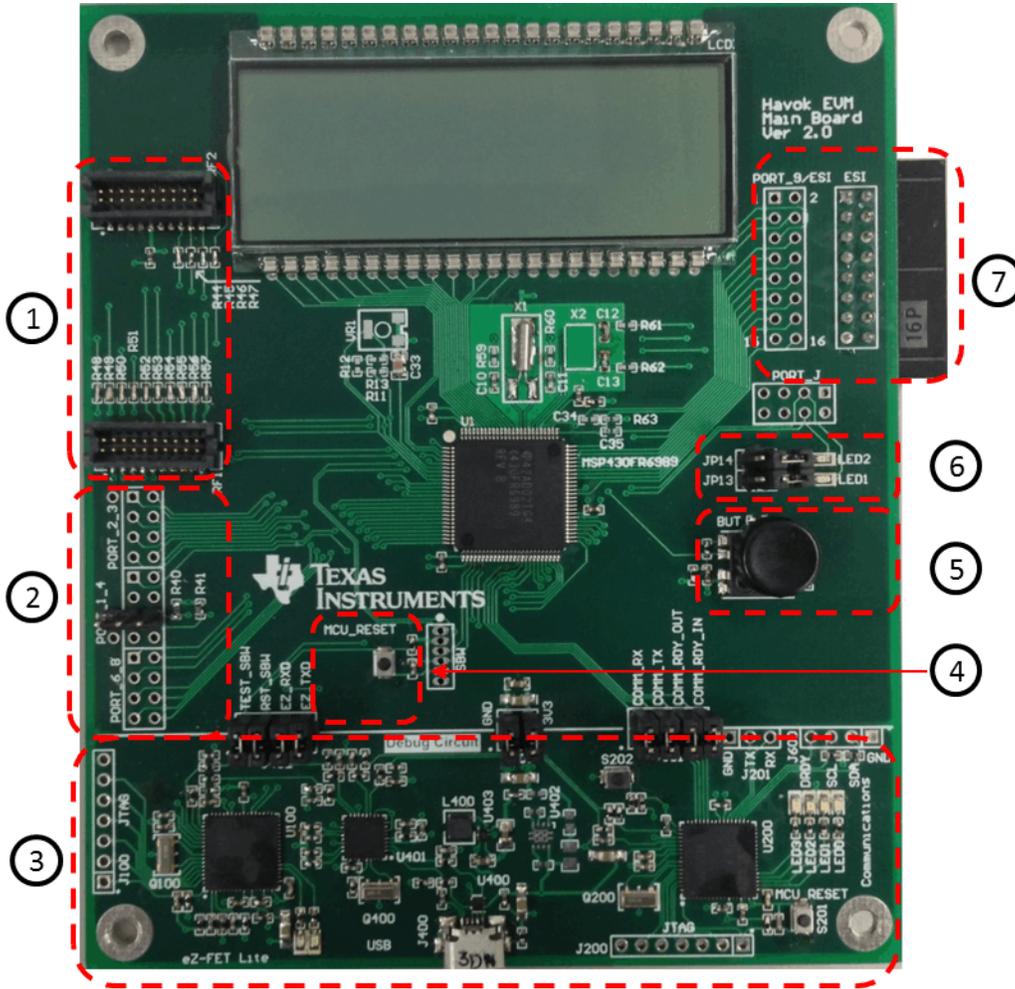


Figure 17. Main Board of EVM

Table 3. Main Board Description

Part 1	A socket for RF modules of sub-1GHz or 2.4GHz, connecting to the MCU with SPI and IO. For details of RF modules, read CC1120 development kit.
Part 2	Through-holes connecting to I/O that are otherwise unconnected. The headers are the I2C connection.
Part 3	The JTAG debugger and a USB HID interface. The HID interface can connect the board to PC with a dedicated GUI.
Part 4	A reset button. This board does not have on/off switch. To re-start the firmware, push the reset button.
Part 5	This device contains five push-button switches. The firmware does not have code for this part. Designers can use it to implement a key control.
Part 6	LED indicator, connected to PJ.2 and PJ.3. To reduce current consumption, remove the jumpers.
Part 7	The socket for the Sensor board to connect to the ESI of the MCU.

### 6.2 Sensor Board

The sensor board is designed for various sensors: LC, GMR, or optical sensors (see Figure 18). On the left part of the board, only LC sensors can be soldered on. The sensors can be placed in different orientation. For half covered metal rotor disc, the sensors are placed in 90° apart. On the right part of the board, GMR and optical sensors can be connected.

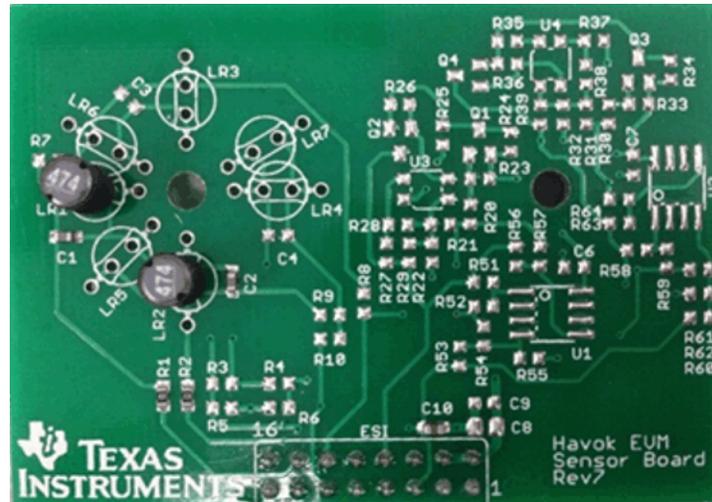


Figure 18. Sensor Board

### 6.3 Motor Board

The motor board is to drive the rotor disc to simulate water or gas flow (see Figure 19). The battery socket is on the back of the board. The parts of the board are described in Table 4.

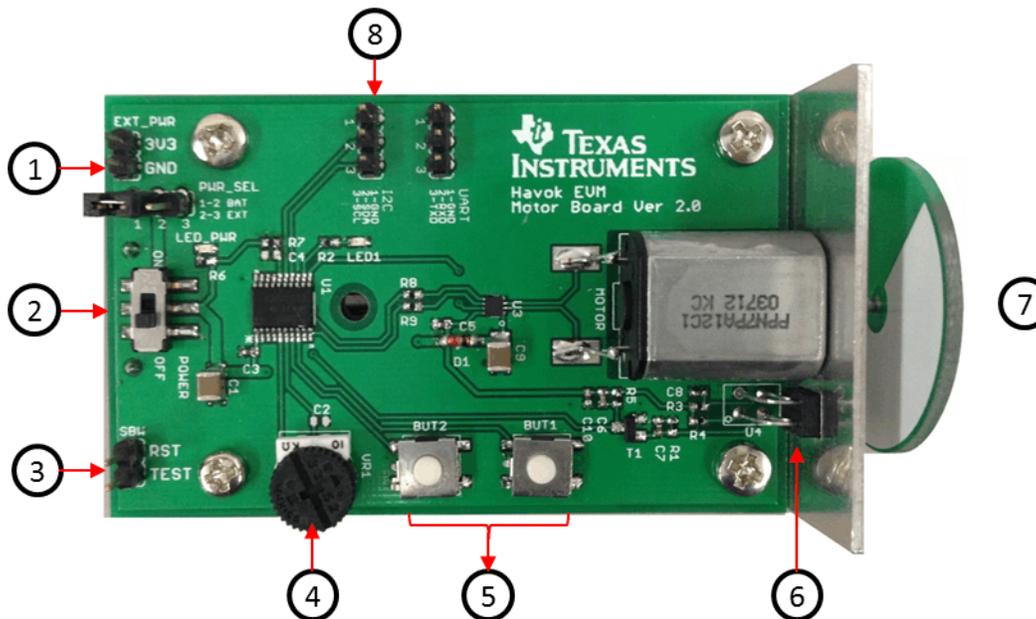


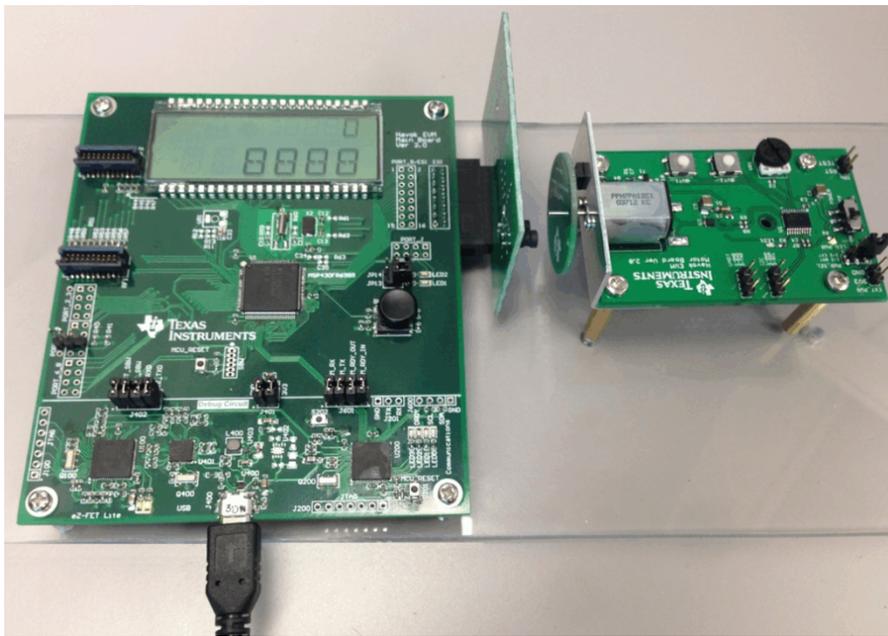
Figure 19. Motor Board

**Table 4. Motor Board Description**

Part 1	Two pins connected to external power
Part 2	Power switch to turn the motor board on or off
Part 3	2-wire Spy-Bi-Wire mode of JTAG. This can be used to program or debug the firmware.
Part 4	Variable resistor to vary the rotation speed.
Part 5	These buttons are to select the rotation direction and also act as a stop button.
Part 6	This is an infrared sensor that provides feedback on the rotation speed of the rotor disc.
Part 7	A rotor disc with half covered by copper.
Part 8	A connection header for I2C and UART.

## 6.4 Demonstration

Figure 20 shows the complete EVM hardware set up to run the demonstration code.



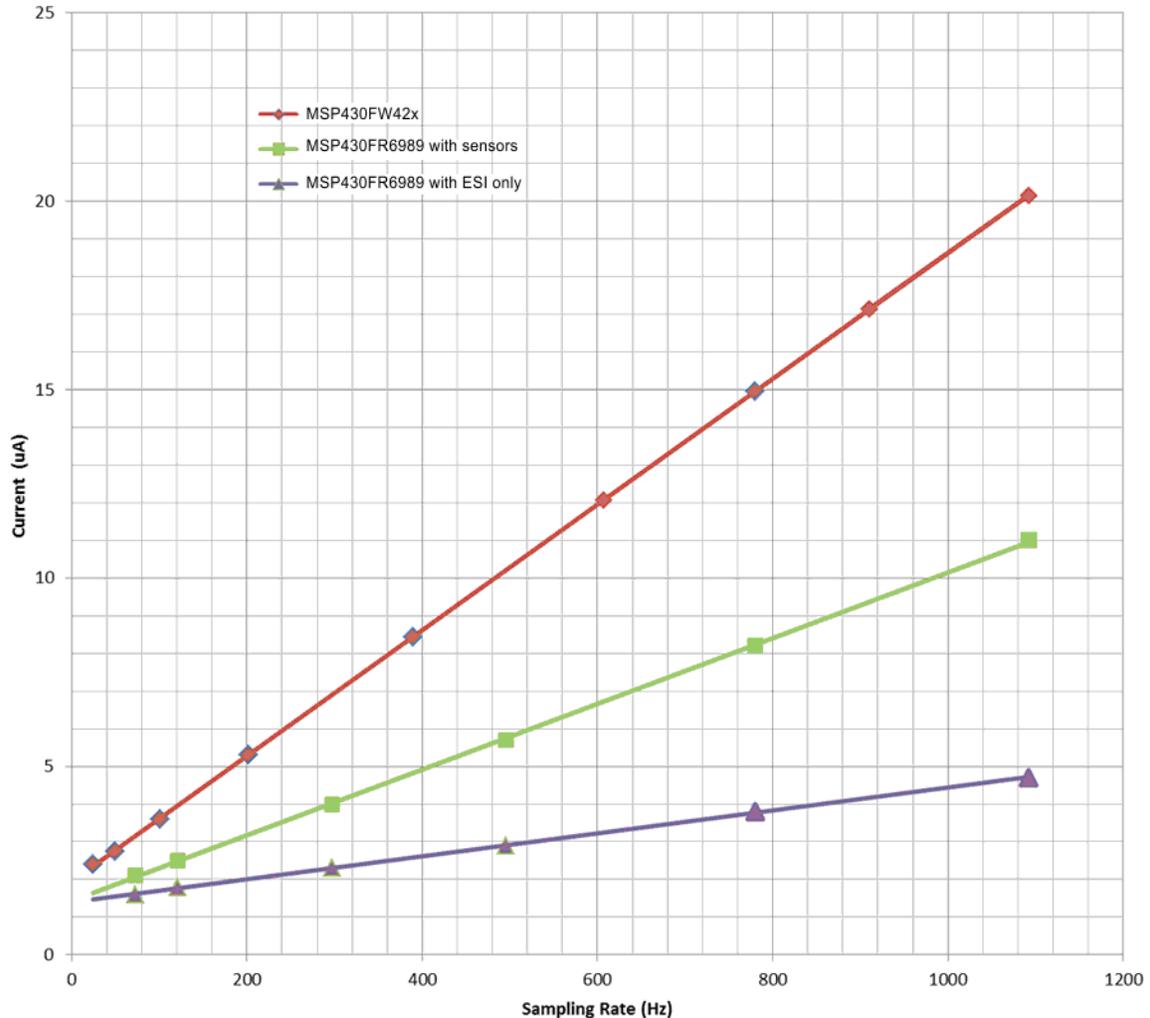
**Figure 20. Complete Evaluation Hardware**

Procedure to use the EVM with Auto-Calibration in initialization of code:

1. Set the rotor at 5 mm from the sensor board and switch off the motor.
2. Power the main board with a USB cable.
3. At start up, a TSM calibration starts and the LCD displays "0". Wait until the LCD displays "8888", then go to next step.
4. Switch on the motor and do not adjust the distance between rotor and sensors. A calibration that determines the proper reference voltages for the DAC starts now and lasts for one second.
5. The initial calibration is now finish. The LCD continues to display the number of rotations.

### 6.4.1 Current Consumption

Figure 21 shows the current consumption of the MCU with two LC sensors, excluding the current into the LCD, power, and other modules on the board. The data is taken by measuring the current flowing into the MCU connected to two sensors with the LCD off, varying with different sampling rate in the SIF of MSP430FW42x and the ESI of MSP430FR6989.



**Figure 21. Current Consumption of ESI With Two Sensors**

From the experimental data, the current consumption in MSP430FR6989 is half of that for a MSP430FW42x system with the same type of LC sensors.

- For the MSP430FR6989 with two LC sensors, the current per sample is less than 9 nA.
- For the MSP430FW42x with two LC sensors, the current per sample is less than 17 nA.

Current consumption of the MSP430FR6989 running the ESI without sensors is also given. This shows that the LC sensors account for half of the total current consumption of the system. To further reduce the current consumption, well designed LC sensors are necessary.



### 6.5.2 FindDAC\_Fast\_Range()

Figure 23 shows the flowchart of FindDAC\_Fast\_Range().

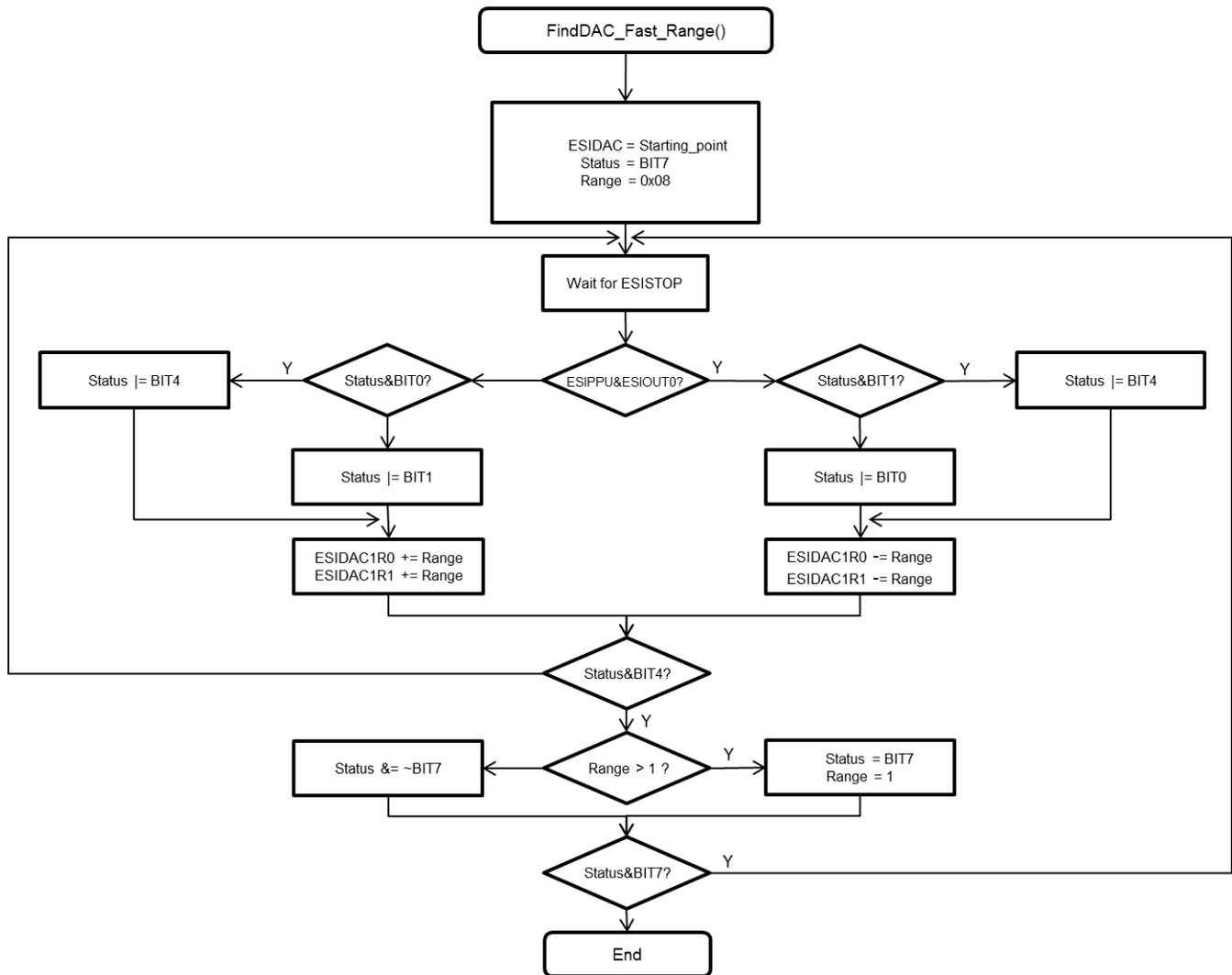


Figure 23. FindDAC\_Fast\_Range Flowchart

6.5.3 AFE2\_FindDAC\_Fast\_Successive()

Figure 24 shows the flowchart of AFE2\_FindDAC\_Fast\_Successive().

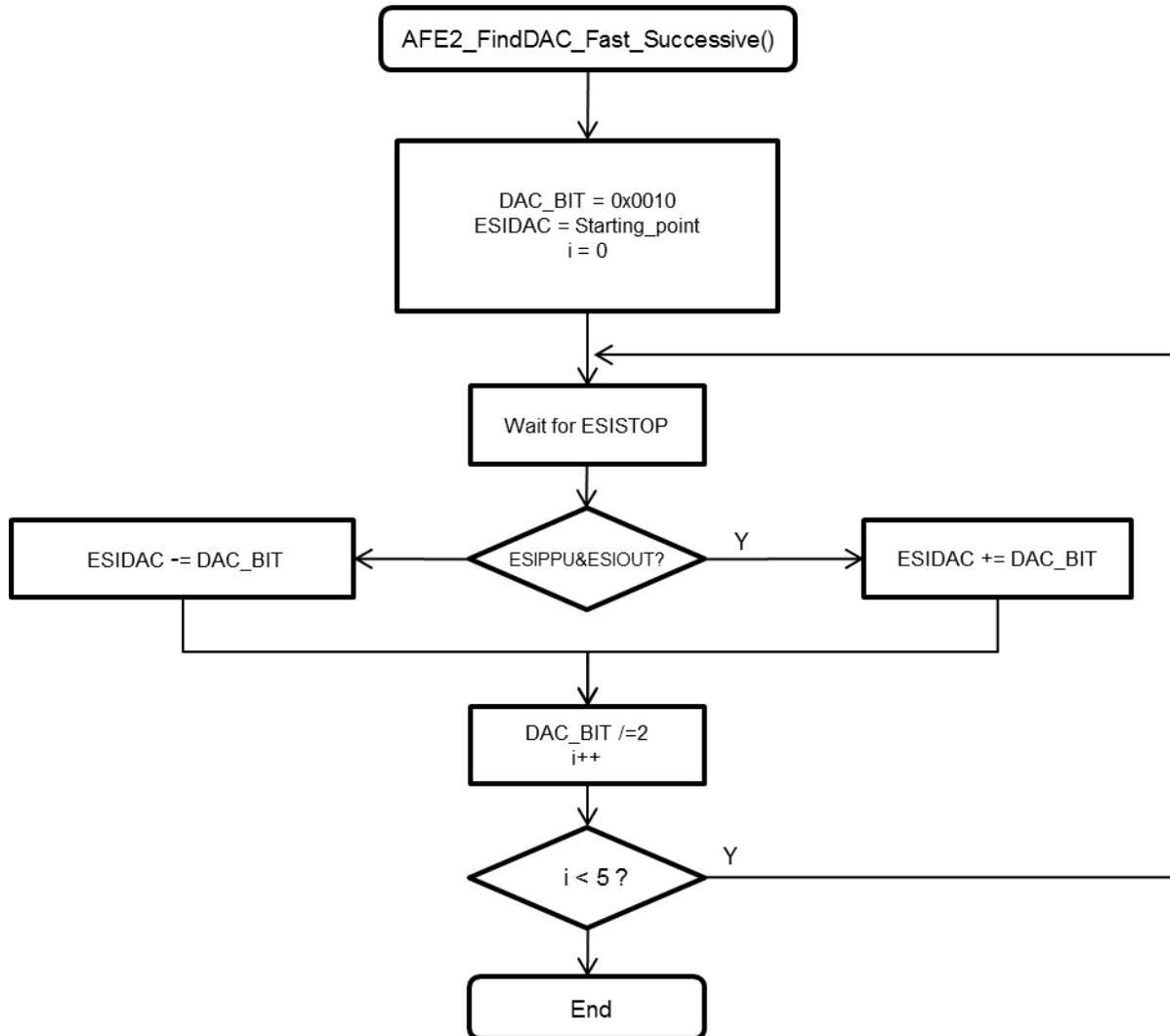


Figure 24. AFE2\_FindDAC\_Fast\_Successive() Flowchart

## 7 References

1. *MSP430FR698x(1), MSP430FR598x(1) Mixed-Signal Microcontrollers* ([SLAS789](#))
2. *MSP430FR58xx, MSP430FR59xx, MSP430FR68xx, and MSP430FR69xx Family User's Guide* ([SLAU367](#))
3. Code Composer Studio ([CCSTUDIO](#)) Version 5.5
4. *Rotation Detection With the MSP430 Scan Interface* ([SLAA222](#))
5. *SmartRF Transceiver Evaluation Board User's Guide* ([SWRU294](#))

## 8 Schematics

The following figures show the schematics of the main, sensor, and motor boards in the EVM430-FR6989.

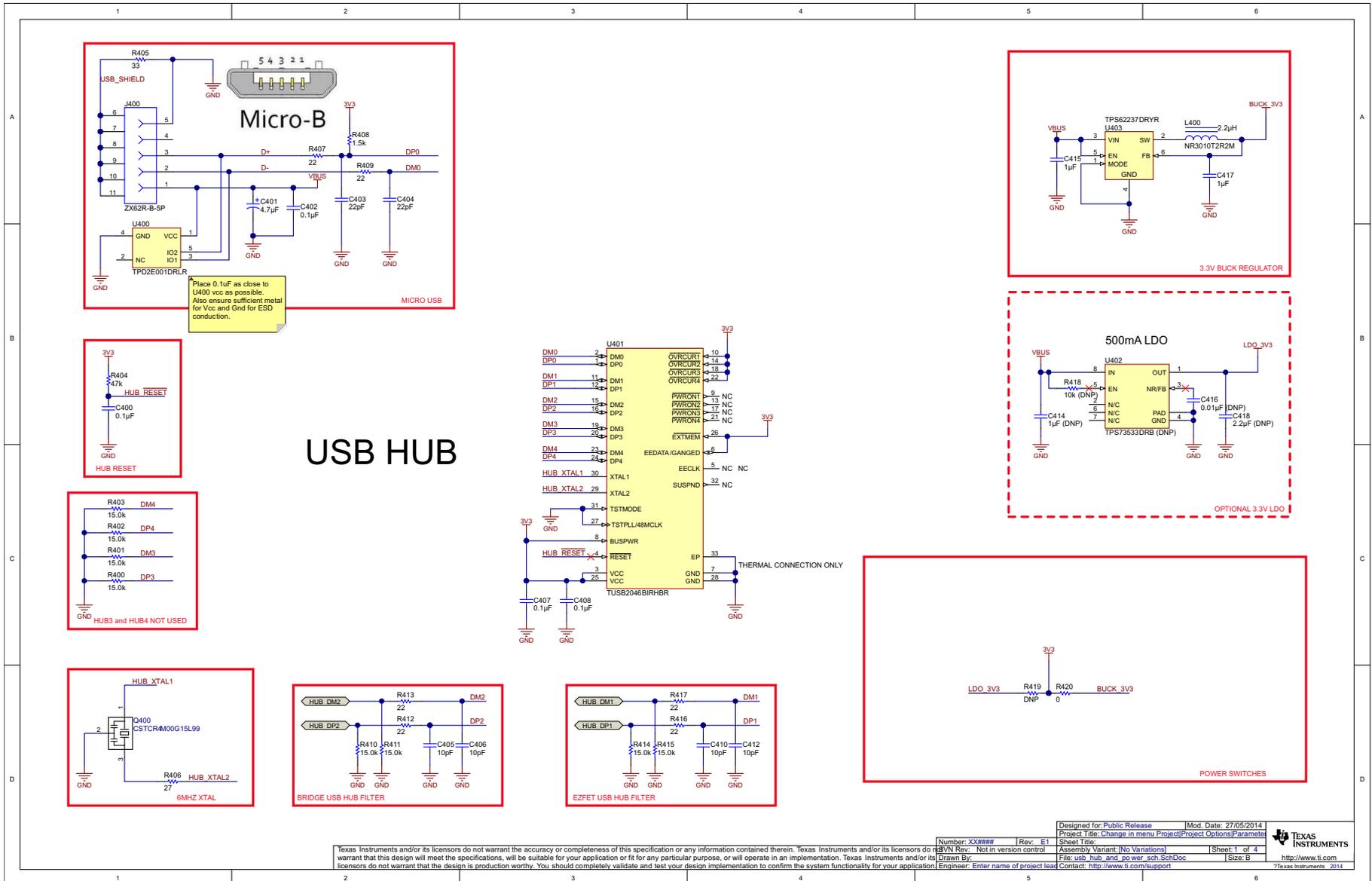


Figure 25. Schematic, Main Board (1 of 4)

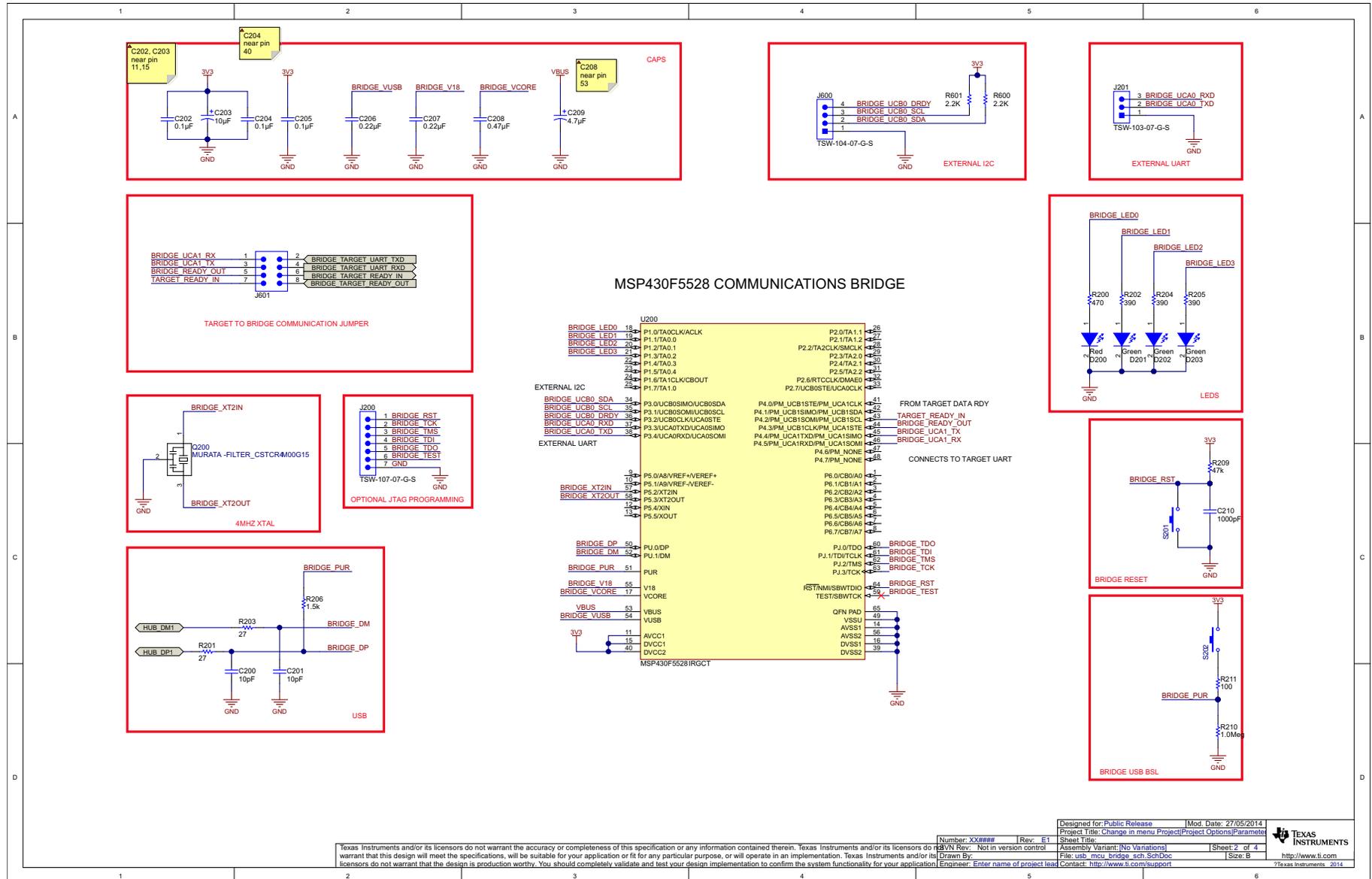
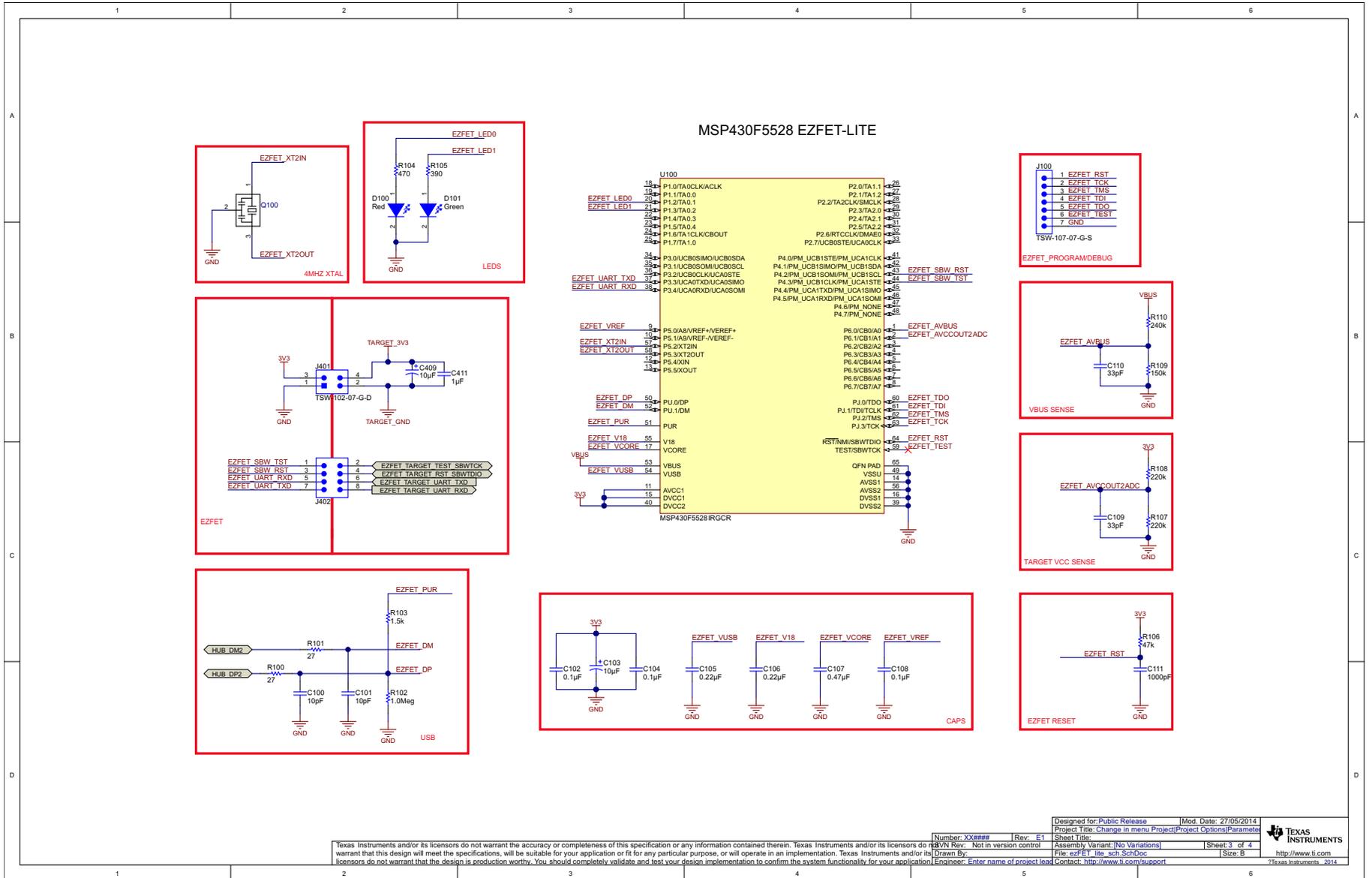
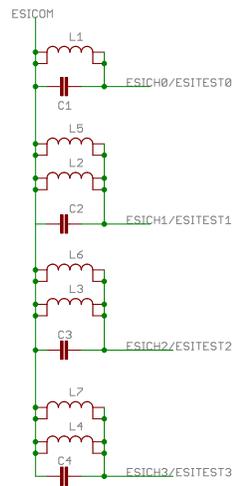


Figure 26. Schematic, Main Board (2 of 4)



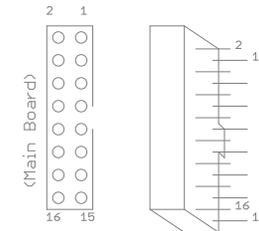
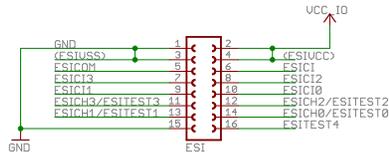




For 2 sensors  
Place L1, L2, C1 and C2 (90 degree separation)  
or L1, L5, C1 and C2 (45 degree separation)  
Uses ESICHO and ESICHI

For 3 sensors,  
Place L2, L6, L7, C2, C3, C4  
Uses ESICHI1, ESICHI2 and ESICHI3

Inductor = 470uH  
Capacitor = 220pF



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**Figure 29. Schematic, Sensor Board**

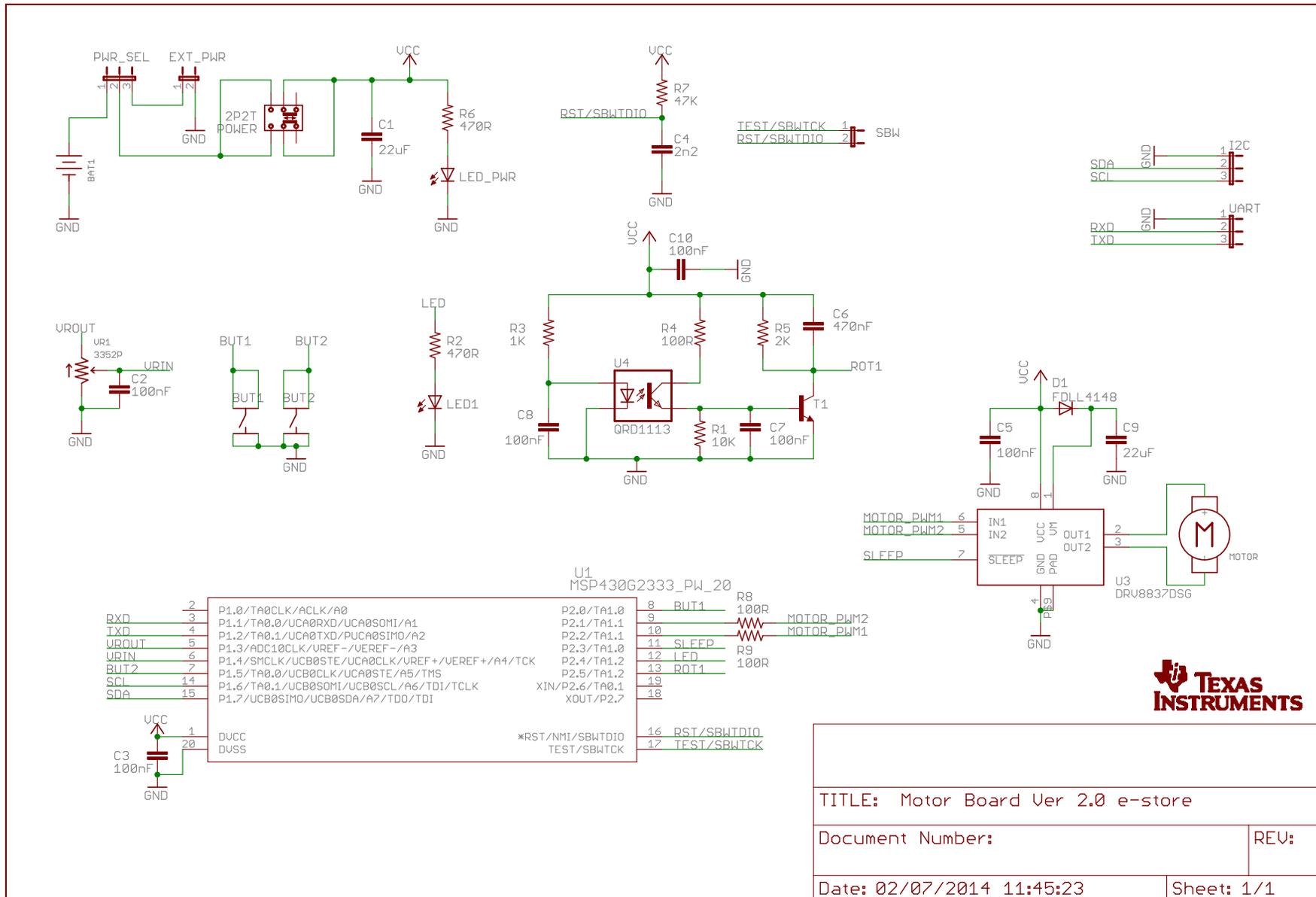


Figure 30. Schematic, Motor Board

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