TI Designs
Air Quality Sensor

Design Overview

Air quality and its effects on health and vitality have recently become a much talked about topic. Higher levels of air pollution have been linked to detrimental health effects and adverse implications on quality of life. The golden standard of measuring the level of air pollution is the Air Quality Index (AQI). In this TI Design, a simple air quality monitor is created and implemented using the particulate matter 2.5 level. This design uses the TI MSP430FR4133 microcontroller in tandem with the Sharp™ DN7C3CA006 PM2.5 sensor. From periodic PM2.5 samples, the AQI is calculated and displayed using an 8-character, 14-segment LCD.

Design Resources

TIDM-AIRQUALITYSENSOR	TI Design Files
MSP430FR4133	Product Folder
HDC1000	Product Folder

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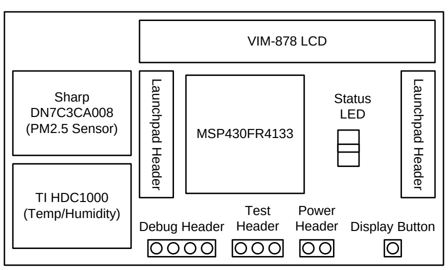
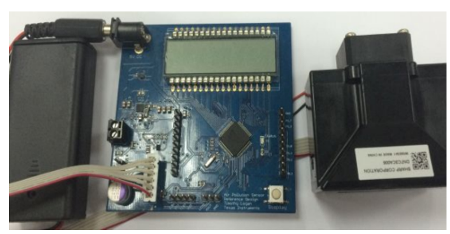
Design Features

- Calculates PM2.5 Concentration Levels and Air Quality Index Levels (AQI)
- Calculates Temperature and Humidity Levels
- Offers an 8-Character, 14-Segment LCD to Display Calculation Results
- Uses an Ultralow-Power MSP430FR4133 Device With an Integrated LCD Controller

Featured Applications

- Air Purifiers
- Weather Stations
- Industrial Systems
- Air Conditioner Systems





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1 Key System Specifications

Parameter	Value	Unit
Voltage In	2.5 to 12	V
PM2.5 Sensing Range	25 to 500	µg/m3
AQI Sensing Range	78 to 500	AQI

2 System Description

TI built the system design to be affordable and flexible. Close scrutiny and great effort was placed into selecting the optimal sensor to calculate the AQI and PM2.5 level. While many sensors can measure particulate matter concentration, the Sharp DN7C3CA006 sensor can measure to a µg/m3 level. Being able to calculate down to the µg/m3 level allows for an accurate calculation of a PM2.5 level rather than a less accurate PM10 level. The measured PM2.5 level is plugged into a specialized equation provided by the US EPA and the AQI is calculated. In addition to PM2.5 and AQI, the integrated TI HDC1000 is used to calculate humidity and temperature. The humidity readings are considered when calculating the PM2.5 level in compliance with the specification in the Sharp data sheet. The AQI can be used to gauge the *healthiness* of the environmental air. Figure 1 shows how the EPA defines various levels of air quality.

Air Quality Index (AQI) Values	Levels of Health Concern	Colors
When the AQI is in this range:	*..air quality conditions are:*	*...as symbolized by this color:*
0-50	Good	Green
51-100	Moderate	Yellow
101-150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Figure 1. EPA Air Quality Index Levels

The obvious applications for this design is use in home appliances and industrial-related applications such as air purifiers. Because developing countries have a significant level of industrialization, measuring air quality reliably and cost effectively is paramount. When the air quality index exceeds a certain threshold, many organizations such as the air quality index of China (AQICN) encourage mask usage (see http://aqicn.org/mask/) to prevent hazardous inhalation of polluted air. A home consumer solution that accurately measures and reports air quality factors provides a significant convenience for residents of developing countries. Consumer air purifiers can also benefit from incorporating air quality sensors into their designs. Instead of an unintelligent and rudimentary air purification algorithm, enhancements can be added to purify air only if the AQI crosses a preset or programmable threshold. This level of intelligence would reduce the overall power consumption of the design by minimizing the duty cycle of the purification mechanism.

2.1 MSP430FR4133

TI chose the MSP430FR4133 MCU due to its low-power operation and integrated segment LCD peripheral. Virtually every peripheral of the MSP430™ is used in this design to foster a complete and optimized architecture. One of the critical advantages of using the MSP430 is the highly configurable and integrated LCD module. Because an 8-character Varitronix VIM-878 segment LCD is used, a microcontroller with 36 LCD I/Os is required. Additionally, the ability of the MSP430 to pragmatically configure which LCD pins are used for SEG lines and which pins are used for COM lines made layout of this design easy. Figure 2 shows the LCD in action.

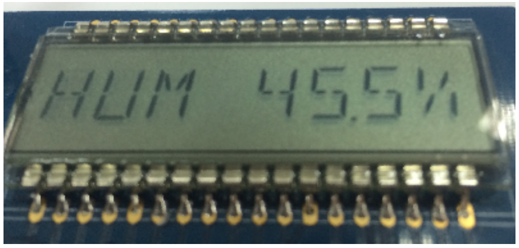

Figure 2. Varitronix VIM-878 LCD in Action

In addition to the LCD module, the low-power centric peripheral set of the MSP430FR4133 allows for a low-power design and power-conscious architecture. The 10-bit ADC module is a perfect companion for the Sharp DN7C3CA006 sensor. The Sharp sensor contains an integrated power amplification system that lets the sensor output integrate easily with the ADC module of the MSP430 without any complicated external circuitry. The intricate and powerful array of timers of the MSP430 allows for a highly configurable and precision timing architecture. In addition to providing a system tick, the timer of the MSP430 also controls the timing pulses for both the Sharp sensor and attached fan. The Sharp sensor has a strict timing requirement of the pulse required to initiate a sample. The Timer_A module of the MSP430 contains a precision PWM feature that makes generating such a pulse easy and intuitive.

2.2 HDC1000

The HDC1000 humidity and temperature sensor perfectly pair with the Sharp DN7C3CA006 sensor. As the Sharp sensor requires a humidity reading for proper calculation of AQI, the low cost and ease-of-use of the HDC1000 made it an ideal component for the design. The HDC1000 uses I^2C communication to report the 14-bit temperature and humidity reading back to the MSP430 host. On the MSP430 side, the I^2C lines connect to the EUSCI lines and a low-power optimized software driver processes the sensor measurements. In addition to displaying air quality readings on the LCD display, the user can display temperature and humidity measurements separately.

3 Block Diagram

Figure 3 shows the block diagram.

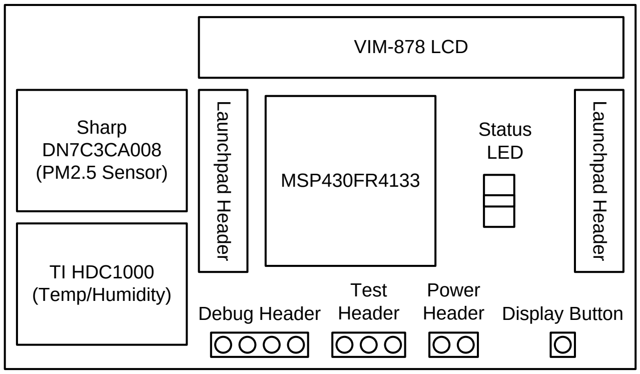

Figure 3. Block Diagram

4 Highlighted Products

4.1 MSP430FR4133

The following are product highlights of the MSP430FR4133 device:

- Embedded microcontroller
- 16-bit RISC architecture up to 16 MHz
- Wide supply voltage range from 1.8 to 3.6 V
- Optimized low-power modes (at 3 V)
  - Active mode: 126 µA/MHz
  - Standby mode: greater than 1 µA with real-time clock (RTC) counter and liquid crystal display (LCD)
  - Shutdown (LPM4.5): 15 nA
- Low-power ferroelectric RAM (FRAM)
  - Up to 15.5KB of nonvolatile memory
  - Built-in error correction code (ECC)
  - Configurable write protection
  - Unified memory of program, constants, and storage
  - 1015 write cycle endurance
  - Radiation resistant and nonmagnetic
- Each LCD pin software-configurable as SEG or COM
- Contrast control from 2.6 to 3.5 V by 0.06-V steps

4.2 HDC1000

The following are product highlights of the HDC1000 device:

- Relative humidity (RH) operating range 0 to 100%
- 14-bit measurement
- Relative humidity accuracy ±3%
- Temperature accuracy ±0.2°C
- 200-nA sleep mode current
- Average supply current:
  - 820 nA at 1sps, 11-bit RH measurement
  - 1.2 µA at 1sps, 11-bit RH and temperature
- Supply voltage 3 to 5 V
- 2-mm × 1.6-mm device footprint
- I^2C interface

5 System Design Theory

5.1 Calibration

The hardware design of the Sharp DN7C3CA006 sensor allows for a method of *self-calibration*. The PM2.5 sensor is housed in a plastic enclosure with an external fan attached. When voltage is applied to the fan, an air sample is drawn into the sensing chamber. A sampling pulse is applied to the ILED pin of the sensor and an analog sample is read through the ADC module of the MSP430FR4133. Figure 4 shows the *air sampling* chamber. Amplification and power compensation of the analog signal occurs internally on the Sharp DN7C3CA006 sensor, eliminating the need for any external amplification or filtering circuitry.

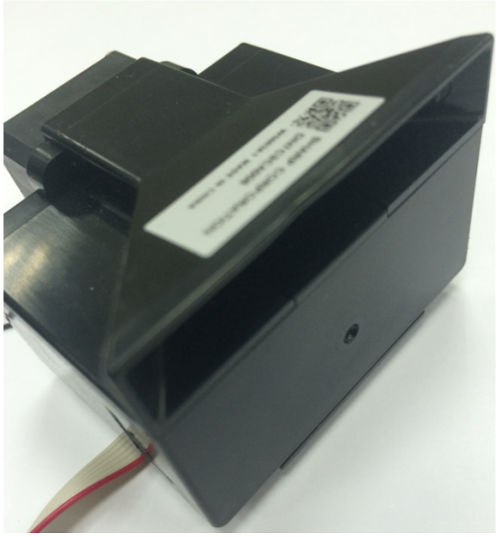

Figure 4. Air Chamber of Sharp DN7C3CA006

The external enclosure allows for self-calibration because a reading can be made without power to the fan. Without power to the fan, the air sample in the chamber is considered *clean* and can be used as a reference or control measurement. This recommendation is consistent with the *control* sampling method from the Sharp data sheet. To achieve power control of the fan, a MOSFET switch was added to the 5-V input to the fan. Section 6.1 shows this system in detail.

5.2 Sampling Method and Frequency

To obtain the most accurate results, the algorithm to sample and record the PM2.5 level was tuned and tweaked after experimentation. By default, the firmware of this TI Design collects 50 samples of PM2.5 each time a measurement occurs. The mathematic mean is calculated from these 50 samples. For PM2.5 and AQI, each measurement occurs every 30 minutes. For temperature and humidity, the measurements occur every 30 seconds. The difference in sampling time is because there is likely less variation in air quality over a short period of time, but the temperature can change rapidly. For each PM2.5 and AQI sample, humidity and temperature samples are also taken because the Sharp sensor requires a humidity sample to accurately calculate the PM2.5 level. Because the sensor adopts a light scattering method for calculation, any environmental humidity in the air must be measured and compensated.

5.3 AQI Calculation

When the PM2.5 has been measured from the Sharp PM2.5 sensor, the AQI is then calculated by the software. Although there are many different variations of air quality metrics, this design uses the one defined by the Environmental Protection Agency (EPA). Figure 5 shows the equation to calculate the AQI from the PM2.5 level.

$$I_P = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(C_P - BP_{Lo}) + I_{Lo}$$

Where I_P is the index for pollutant p

C_P is the rounded concentration of pollutant p

BP_{Hi} is the breakpoint that is greater than or equal to C_P

BP_{Lo} is the breakpoint that is less than or equal to C_P

BP_{Hi} is the breakpoint that is greater than or equal to C_P

I_{Hi} is the AQI value corresponding to BP_{Hi}

I_{Lo} is the AQI value corresponding to BP_{Lo}

Figure 5. Equation for Calculating AQI

The *breakpoints* in Figure 5 are hardcoded as float values into the firmware of the design. These breakpoints were taken from the technical reference document of the EPA and represent the individual *thresholds* of the different levels of air quality. After the PM2.5 level is calculated, the code goes through these breakpoints individually and determines the appropriate thresholds to use. From these thresholds, the AQI is calculated and displayed on the LCD screen.

6 Getting Started Hardware

6.1 Power Circuitry

The power circuitry of this TI Design was made to advocate ultralow-power applications. Two power rails are required: one 3.3-V rail for the MSP430FR4133 and one 5-V rail for the Sharp DN7C3CA006 sensor. The 3.3-V rail was increased to a 3.4-V rail to compensate for the maximum analog sampling output of the Sharp DN7C3CA006 sensor. The 3.4-V power rail is supplied by the TPS715345 low-dropout linear regulator. This regulator provides a wide operating voltage range (2.5 to 24 V) in addition to a low-quiescent current of 0.003 mA. While the 3.4-V rail can handle up to 24 V, the 5-V rail can only handle up to 12 V, limiting the overall maximum input system voltage to 12 V.

For the 5-V power rail, TI chose the TI TPS63061 buck-boost converter. This IC provides a steady and fixed 5-V signal when provided a voltage range from 2.5 to 12 V. The input of the power connector of the design is a 2.1-mm barrel jack connector that lets the user easily connect anything from a 5-V USB connection to a wall DC supply within the given range. Although this IC is certainly versatile, because of the advanced WSON10 package, care must be given to the layout. Because the 5-V power rail is a buck-boost converter, selecting an inductor must be a careful process. For this design, TI chose a TDK 1-µH inductor and gave special considerations to the layout and placement proximity to the TPS63051. Figure 6 shows the example layout of this configuration.

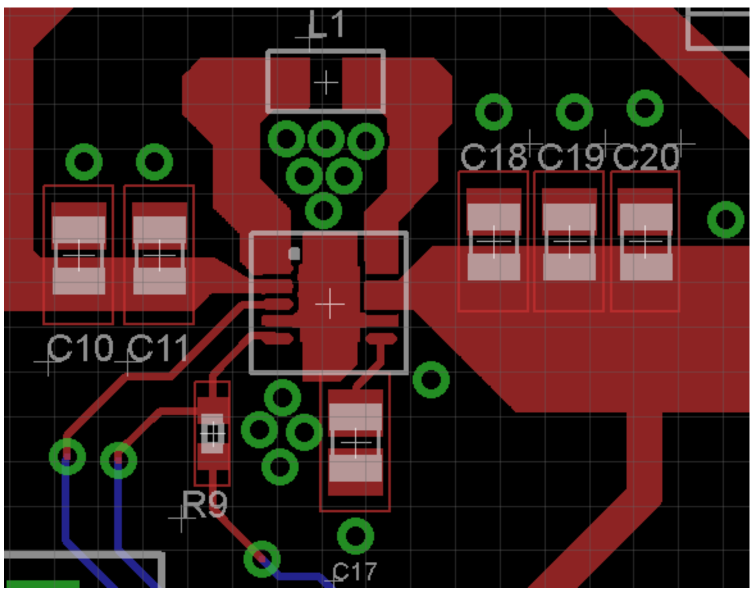

Figure 6. Layout of TPS63061 Buck-Boost Converter

The fan of the PM2.5 sensor is controlled by a simple N-channel MOSFET switch. Because the current of the fan is defined by the data sheet to be 140 mA, the low-power oriented application must power on the fan as little as possible. Using the MOSFET switch, the 3.3-V GPIO output of the MSP430 can effectively toggle the 5-V output of the fan of the PM2.5 sensor. The ground output of the fan is connected to the drain of the MOSFET. The gate is connected to the MSP430 and the source is connected to ground. This connection allows the MSP430 to complete the circuit (turn on the fan) by driving the gate pin high and turn off the fan by driving the pin low.

6.2 Display Button and LaunchPad™ Headers

This design can change between different display modes. These display modes represent the different measurements that are made on the system. On power up, the default power mode is AQI. In addition to AQI, temperature, humidity, and raw PM2.5 data can also be displayed. Each press of the *display* button cycles between the display modes. Table 1 lists the various display modes and the appropriate units.

Table 1. Display Modes

Display Mode	Source	Unit	Notes
Temperature	HDC1000	°C	Defaults to updating every second.
Humidity	HDC1000	Percentage	Defaults to updating every second.
PM2.5	DN7C3CA006	$\mu g/m^3$	PM2.5 level calculated from analog sample before using the AQI formula.
AQI	DN7C3CA006	US AQI	AQI as defined by the EPA

This design has LaunchPad headers. TI placed these headers as potential expansion ports as well as debug access to the MSP430. Although all of these headers are not populated, certain key headers are populated to allow serial access and give the opportunity for future firmware updates. For example, wireless communication through a wireless booster pack would be possible through added functionality in the firmware update.

7 Getting Started Firmware

7.1 System and Timer Configuration

The firmware of this TI design uses every peripheral on the MSP430FR4133. TI built the firmware in a modular and organized fashion. Each timer in the system has a specific and targeted function. Table 2 lists each timer and the corresponding function. Table 3 lists each clock source and signal.

Table 2. Timer Configurations

Timer	Function
WDT_A	Watchdog mode with 3-second time-out period
RTC	System tick that periodically wakes up main application, services watchdog, and kicks off a new sensor reading
TIMER_A0	Used to turn on the fan of the PM2.5 sensor for a few seconds before initiating sensor reading
TIMER_A1	Used to send timing pulse to PM2.5 sensor and kick off ADC sampling

Table 3. Clock Sources and Signals

Clock Source	Frequency
MCLK/SMCLK	8-MHz (maximum without introducing wait states) source from REFO
ACLK	32-kHz source from LFXT

7.2 Main Sensor Interaction Code

The main sensor code is organized in a standard while main loop setup. The main.c file of the firmware has an infinite while loop. At the end of this loop is an entry to low-power mode. The firmware periodically wakes up the device to perform tasks such as reading the sensor and servicing the watchdog. The RTC timer is used for the system tick and to service the watchdog timer at the beginning of every tick. In the interrupt handler for the RTC, a new sensor reading is initiated based on the display mode and the device is put into low-power mode. When the sensor reading completes, the device exits low-power mode and the main loop handles any post processing or LCD display logic.

For calculating AQI and PM2.5, special timing considerations must be taken to ensure low-power optimized operation. Because the power of the PM2.5 sensor fan is relatively high compared to the MSP430, the fan should be on as infrequently as possible. Whenever a PM2.5 or AQI sample is made, TIMER_A0 is used to *ramp* on the fan for a few seconds before the actual sampling algorithm is initiated (see the **Section 5.3** for details on this algorithm). Figure 7 shows a block diagram of this basic software flow of calculating the PM2.5 or AQI. When calculating AQI or PM2.5, the first sample is taken with the fan off to obtain a *reference* measurement of a clean sample of air. During this time, a value of *CAL* displays on the LCD screen.

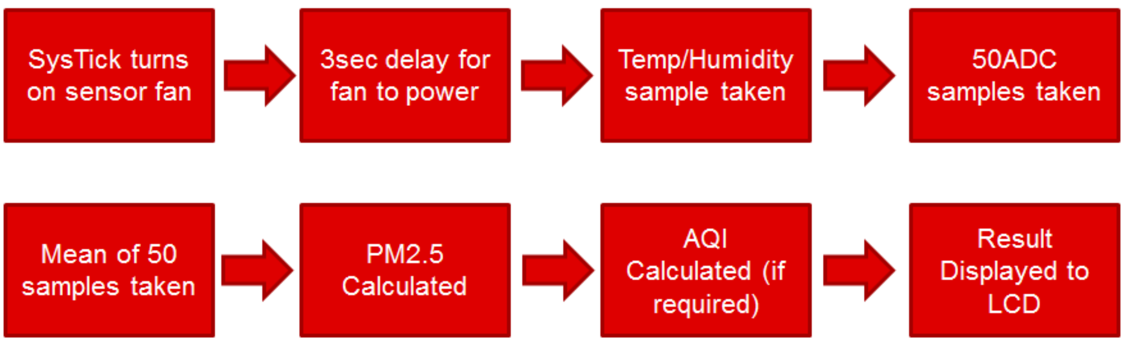

Figure 7. PM2.5 and AQI Calculation Algorithm

7.3 Varitronix VIM-878 LCD Driver

The Varitronix VIM-878 LCD driver is programmed to be modular and easily reused by other applications. The vim878_initializeDevice function contains the code for configuration and initialization of the LCD module of the MSP430. When porting to other applications, this function must be modified to correspond with the correct COM and SEG pin settings. Aside from initialization, two additional user level functions exist with the LCD driver: vim878_displayString and vim878_displayChar. The string function takes in a constant array of characters and displays the string to the LCD screen (with an offset option available). The character function performs the same function, but this function accepts only one character. For these functions, the acceptable character values are capital A–Z, numerical 0–9, and the percentage sign (%). Input of any other characters results in unreliable and incorrect display.

7.4 HDC1000 Temperature and Humidity Driver

TI made the HDC1000 software driver to be highly configurable and easily reusable for other applications. The HDC1000 sensor can be configured through the hdc1000_configureDevice function to have different resolution results for both the temperature and humidity. The HDC1000 sensor can also be configured to enable or disable the integrated heater. This function also contains the pin configuration for interrupts as well as configuration of the eUSCI_B I2C peripheral. Users porting this code to a different application must modify the hdc1000_configureDevice function to match the design of their application.

After calling the hdc1000_configureDevice function with the desired settings, call the hdc1000_initiateMeasurement function to start a temperature and humidity reading. This function is nonblocking and returns control to the application after initiating the reading. When the HDC1000 sensor has a temperature and humidity result, it asserts the GPIO pin to the MSP430. The application handles this interrupt and calls the hdc1000_startReadResult function to initiate the I^2C reading of the measurement result. This function accepts one parameter called *wakeup* that is passed by the EUSCI I^2C interrupt into the __bic_SR_register_on_exit function upon a successful reading of the temperature and humidity result. The application then calls the hdc1000_getResult to get the final measurement result.

8 Test Data

TI used practical and real-life environmental testing on this design. TI developed this design in Shanghai, China, which allowed for testing at various levels of air quality. Measurements were also gathered in other countries such as India and Japan to record a wide range of measurement data. In each use case, TI performed and recorded PM2.5, AQI, temperature, and humidity measurements.

Two *control* measurements were also taken inside an office environment as an added sanity test. For the first control measurement, a simple measurement was taken indoors with no external stimulus. For this measurement, the PM2.5 reading was less than the threshold of the Sharp sensor and a value of LOW displayed on the LCD screen. For the second control measurement, a candle was lit and extinguished during the sampling period and the smoke wafted into the air sensor chamber. In this measurement, the PM2.5 value was saturated on the sensor and a value of HIGH displayed on the LCD screen. Table 4 lists the full array of test results including temperature and humidity measurements.

Table 4. Air Quality Test Data

Environment Setting	Temperature	Humidity	PM2.5	AQI	Notes
Inside office	24.1°C	52.70%	Low	Low	Performed in closed office room with windows closed. Measurement was so low that it was less than the lower threshold of the sensor.
Candle smoke	24.1°C	52.70%	High	High	Candle lit and smoke was fed into sensor during sampling. Measurement was so high that it went higher than upper threshold of the sensor.
Outside—Good day	23.2°C	52.20%	Low	Low	Measurement taken in Tokyo, Japan when AQICN was reporting an AQI of 35. Measurement was so low that it was less than the lower threshold of the sensor.
Outside—Good Day Test 2	33.9°C	48.5%	Low	Low	Measurement taken in Bangalore, India at the parking lot of the TI office. Data for this location is not recorded publically online and therefore cannot be compared to any standard.
Outside—Moderate Day	29.3°C	43.2%	38	108	Measurement taken in Shanghai, China when AQICN was reporting an AQI of 98.
Outside—Unhealthy for sensitive day	10.6°C	51.40%	39	111	Measurement taken in Shanghai, China when AQICN was reporting an AQI of 114.

Table 4. Air Quality Test Data (continued)

Environment Setting	Temperature	Humidity	PM2.5	AQI	Notes
Outside—Unhealthy	17.7°C	45.60%	113	181	Measurement taken in Shanghai, China when AQICN was reporting an AQI of 164.
Outside—Very unhealthy day	18.2°C	44.90%	213	263	Measurement taken in Shanghai, China when AQICN was reporting an AQI of 253.

9 Design Files

9.1 Schematics

To download the Schematics for each board, see the design files at http://www.ti.com/tool/TIDM-AIRQUALITYSENSOR.

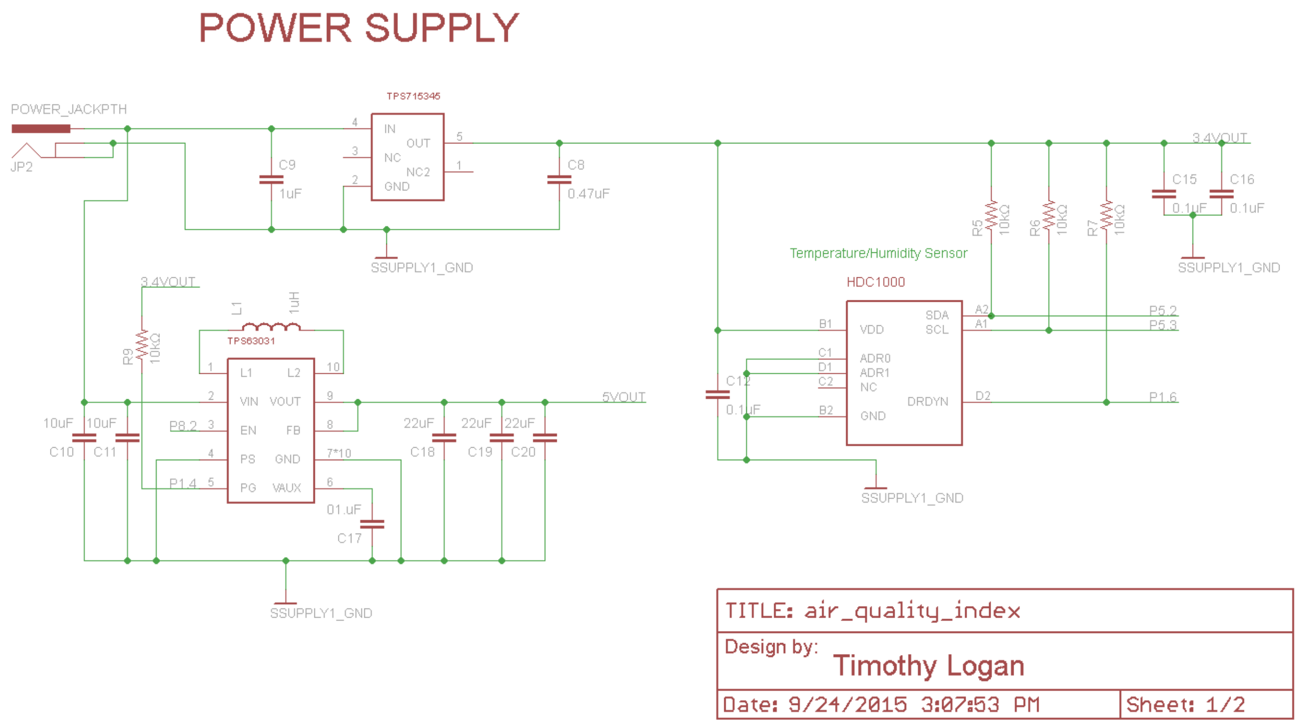

Figure 8. Schematics Page 1

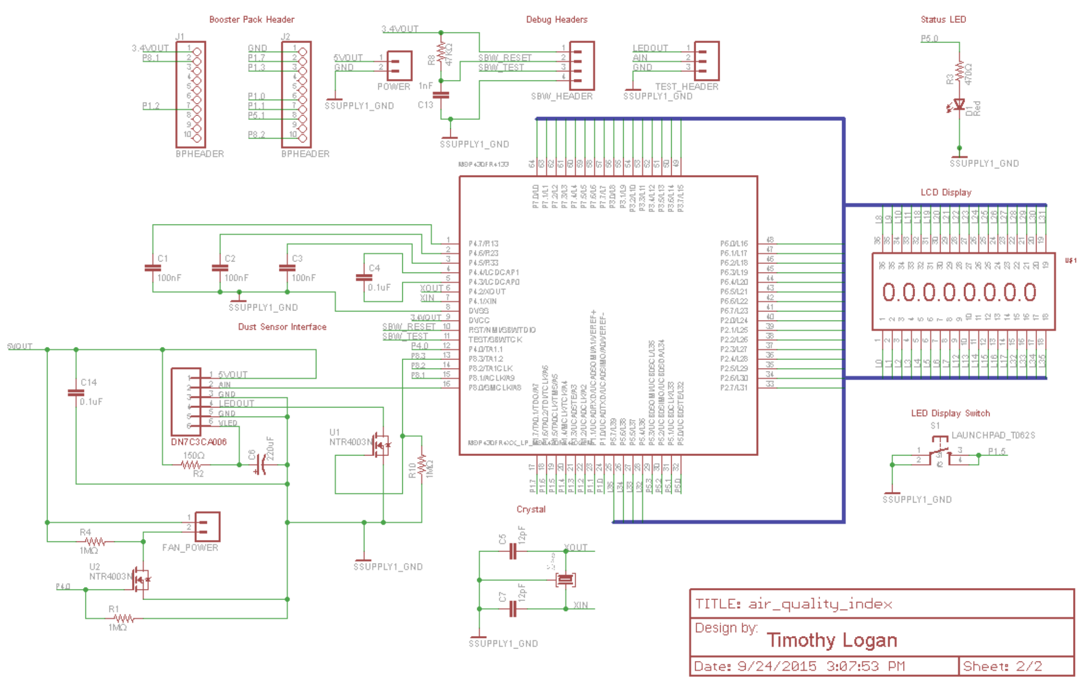

Figure 9. Schematics Page 2

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at http://www.ti.com/tool/TIDM-AIRQUALITYSENSOR.

Table 5. BOM

Item	Quantity	Reference	Value	Part Description	Manufacturer	Manufacturer Part Number
1	7	C1, C2, C3, C4, C14, C15, C16	0.1 µF	0.1µF 16 V X7R 10%	Murata	GRM155R71C104KA88D
2	2	C5, C7	12 pF	12 pF 25 V C0G 5%	Murata	GRM1555C1E120JA01D
3	1	C6	220 µF	16 V 220 µF ESR 13 mΩ	Panasonic	16SEPC220MD
4	1	C8	0.47 µF	0.47 µF 10 V X5R 10%	Murata	GRM155R61A474KE15D
5	1	C9	1.0 µF	1.0 µF 6.3 V X7R ±10%	Murata	GRM155R70J105KA12D
6	2	C10, C11	10 µF	10 µF 10 V X7R 10%	Murata	GCM21BR71A106KE22L
7	2	C12, C17	0.1 µF	10 V 100 nF 5%	Taiyo Yuden	LMK212SD104JG-T
8	1	C13	0.001 µF	0.001 µF 10 V 10%	Murata	GRM155R61A102KA01D
9	3	C18, C19, C20	22 µF	22 µF 10% 16 V	TDK Corporation	C2012X5R1C226K125AC
10	1	D1	Red	Standard LEDs – Hyper Red	Lite-On	859-LTST-C170TBKT
11	1	DEBUG_HEADER	1X04	4POS .100" STR TIN	Molex	901200124
12	1	DN7C3CA006_HEADER	JST-5-PTH	6 header connect for JST	JST	B6B-XH-A(LF)(SN)
13	1	FAN_POWER	3.5MM-2	Screw Terminals 3.5-mm Pitch	On Shore	OSTTE020104
14	2	J1, J2	1×10	10POS .100" STR TIN	Molex	901200130
15	1	JP2	2.1 mm	Conn power jack 2.1-mm PC	Cui	PJ-202A
16	1	L1	1 µH	FIXED IND 1UH 800MA	TDK Corporation	MLP2012S1R0T
17	1	POWER_HEADER	1X02	2POS .100" STR TIN	Molex	901200122
18	3	R1, R4, R10	1M Ω	1 MΩ 1%	Yageo	RC0805FR-071ML
19	1	R2	150 Ω	150 Ω 5%	Yageo	RC0805JR-07150RL
20	1	R3	470 Ω	470 Ω 1%	Yageo	RC0805FR-07470RL
21	4	R5, R6, R7, R9	10 MΩ	10 kΩ 1%	Yageo	RC0402FR-0710KL
22	1	R8	47 kΩ	47 kΩ 1%	Yageo	RC0402FR-0747KL
23	1	S1	T062S	Switch tactile SPST-NO 0.05A 24 V	Omron	B3S-1000P
24	1	TEST_HEADER	1X03	3POS .100" STR TIN	Molex	901200123
25	1	TPS63061	WSON10	2.5 to 12 V Buck-Boost Converter	TI	TPS63061DSCR
26	1	VIM-878	VIM-878	LCD 14SEG 8DIG 0.275" TRANSF STD	Varitronix	VIM-878-DP-FC-S-LV
27	1	HDC1000	DSBGA8	Digital Humidity/ Temperature Sensor	TI	HDC1000YPAT
28	1	TPS715345	SC70-5L	50 mA, 24 V, 3.2-µA Iq, LDO	TI	TPS715345DCKR

Table 5. BOM (continued)

Item	Quantity	Reference	Value	Part Description	Manufacturer	Manufacturer Part Number
29	1	MSP430	MSP430FR4133IPMR	16 MHz MCU 16 KB FRAM, 2 KB SRAM	TI	MSP430FR4133IPMR
30	1	X1	32.768 kHz	32.768 kHz, ±20 ppm, 12.5 pF, –40°C +85°C	ABRACON	AB26TRQ-32.768kHz-T
31	1	DN7C3CA006	Module	MOD PM2.5 DUST SENSOR	Sharp	DN7C3CA006
32	2	U1, U2	BSN20-7	MOSFET NFET 30 V .56 A 1500 M	ON Semiconductor	BSN20-7

9.3 *EagleCAD Project*

To download the EagleCAD project files for each board, see the design files at http://www.ti.com/tool/TIDM-AIRQUALITYSENSOR.

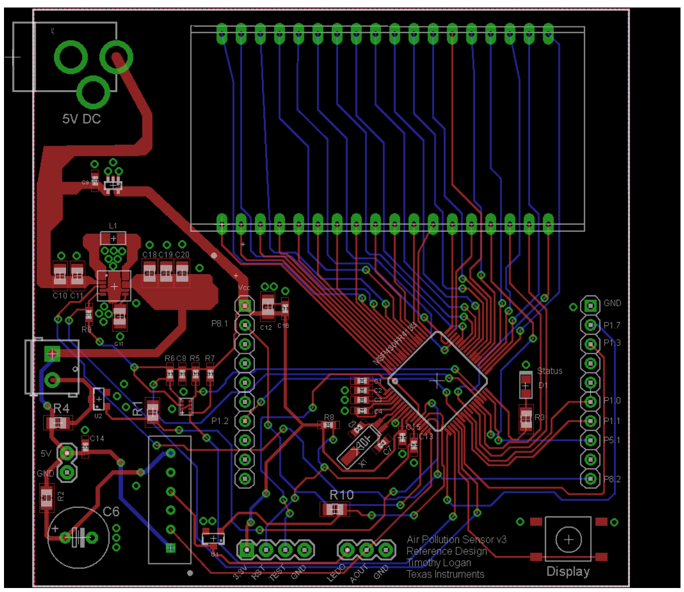

Figure 10. Design Layout

9.4 *Gerber Files*

To download the Gerber files for each board, see the design files at http://www.ti.com/tool/TIDM-AIRQUALITYSENSOR.

9.5 *Software Files*

To download the software files for each board, see the design files at http://www.ti.com/tool/TIDM-AIRQUALITYSENSOR.

10 References

1. *Airnow.gov, Air Quality Index (AQI) Basics, 2015,* http://airnow.gov/index.cfm?action=aqibasics.aqi
2. *Environmental Protection Agency, Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI), 2013.*, http://www.epa.gov/airnow/aqi-technical-assistance-document-dec2013.pdf

11 About the Author

TIMOTHY LOGAN a software engineer at TI where he develops ARM® Cortex® M and MSP430 software. Timothy brings to this role his extensive experience in embedded programming as well as high-level object-oriented programming expertise. Timothy earned his Bachelor of Science in Computer Engineering (BSCE) from Texas Tech University in Lubbock, TX.

Revision History

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

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

- Updated first paragraph of Test Data section. 11
- Updated Air Quality Test Data Table. 11

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