

Wireless Sensing System for Intelligent Concrete Curing



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**TEXAS
INSTRUMENTS**

Executive Summary

The motivation behind this project stems from the uncertainty of time required for concrete to completely settle. A strong economic potential presents itself, especially in the commercial industry, for devising a product that will accurately tell a customer when a new pour is ready to be worked on. Construction companies give their best estimate when concrete is fully settled, but if there was a product that would pinpoint an exact time for curing it would cut down on time and money wasted.

Texas Instruments requested a sensing module that is compatible to their new introduced prototyping platform, MAVRK. Our prototype connects to the μ MAVRK, a remote monitoring system that wirelessly transmits to the motherboard, MAVRK. The sensing module contains a temperature and humidity sensor that undergoes signal conditioning to the MSP430 microprocessor. Each of the sensors is resistive components that use a supplied current to create a voltage drop across them. As the two parameters change, a linear change in voltage is produced that is filtered and amplified through various amplifiers. A boost converter and a voltage regulator are utilized to provide a required consistent voltage to the sensors for functionality. The signals are converted to a digital representation in the processor that is sent to a transceiver that is synced with the MAVRK. Both the motherboard and the monitoring system are programmed via debugging modules, to properly interpret the transmitted signals in a graphical user interface.

This specific design offers one more of many applications provided by the MAVRK system making it even more marketable. What makes the MAVRK appealing is the ability for users to compute system-level design with multiple configurations of RF, signal conditioning, AD/DA conversion and transceiver modules.

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Chapter 1: Introduction and Project Background

1.1 Introduction

Concrete work, whether residential or commercial, is a costly investment that can impede on one's business or personal convenience during the curing process. Construction companies give an arbitrary duration of time to customers when they will be able to begin utilizing their investment. A 28-day strength diagram has been developed to estimate the time in which concrete has fully matured to offer its optimal strength. However, the maximum strength can be reached at different times based on ambient temperatures and humidity concentration in the environment and in the concrete. Hydration process is the chemical reaction that takes place in concrete, where the Portland cement reacts with water to form crystals that bonds and hardens the material. If concrete is poured in cold environments with temperatures less than 40 degrees Fahrenheit, the reaction will seize, causing the concrete to not settle properly and essentially freeze. High temperatures evaporate the water content too fast leaving the crystals with an insufficient amount of water to form uniformly throughout the concrete causing cracks. Given these varying set-up times, it would be very beneficial to know the exact time the concrete is cured to optimize business production and ensure maximum strength in a structure.

Texas Instruments has taken interest in designing a system that would relay information of two important parameters, temperature and humidity, to a customer that would inform them when they could begin utilizing their product. The desired specifications for this particular project are to produce wireless communication from the sensors that have been dispersed throughout the freshly poured concrete, to a centralized unit. This unit will calculate, through an algorithm, when the concrete is cured based on the information presented. The most imperative constraints for optimizing the designed system are power, accuracy, range and cost. Sensing modules must possess enough battery life to be able to transmit signals for the slowest settling times of concrete, established as three weeks. These signals need to have enough power to reach the centralized unit without any distortion in the information, and relay accurate levels. To guarantee that this product will be of economic benefit to TI, it needs to be competitive with similar products currently on the market.

1.2 Background

This idea has received plenty of attention over the past 15 years. Research papers such as, “Feasibility of Embedded Wireless Sensors for Monitoring of Concrete Curing and Structural Health,” by B. Quinn and G. Kelly, have concluded that these sensing units are very achievable. Currently, there are limited companies, such as Engius who developed IntelliRock systems that have released similar sensing units with varying amenities. The basis of these units require one to drill holes (5” by 1” diameter) in the hardened concrete in numerous areas, placing sensors in the holes that connect to a unit that receives information on temperature and humidity. The information about those parameters is then used to calculate when the concrete is properly cured from a central display unit. Mobility and excessive work for implementation of the product are two major problems with these modules. The sensors are connected via wires to the central unit, constraining the product to only being able to test a small area of the concrete at one time. The other problem presented is the amount of time and work spent drilling and placing the probes in multiple regions for testing, then gathering the data from each section and computing the development of the concrete.

CAS Dataloggers is a company that specializes in manufacturing various data acquisition systems. While they do not currently produce a logging system that incorporates both humidity and temperature, they do offer them as individual entities. Other relevant systems to concrete they have are, wireless data loggers and a concrete maturity logger. This very precise maturity logger calculates concrete maturity through a product of temperature and time. Maturity can therefore be correlated to computing the strength of concrete. This particular product is very appealing in the construction industry but comes with a very high cost, and along with the IntelliRock system, these wired systems do not offer high mobility.

These complications have inspired alternate options for a more efficient solution. Wireless sensing systems have been researched and developed to combat the issue, but come at a higher cost than wired systems. Texas Instruments is taking a new approach, by making a mobile transmitting system at a more feasible cost, that when completed has a great potential of generating strong revenue.

Chapter 2: Exploring Solutions and Selecting an Approach

2.1 Solution Exploration

In the design stage of any product, there exists numerous execution paths that will ultimately lead to the same destination of a fully function solution. While having flexibility in an approach is beneficial, narrowing down the optimal route can be very challenging. Identifying customer constraints is a very operative method to ensure success. Our team implemented certain methodical devices that Six Sigma employs that directed us towards a relevant prototype.

2.2 Fast Diagram

Six Sigma is a systematically driven approach companies employ daily to ultimately reduce the possibility of error from manufacturing to service. In every aspect of a business there exists a derived model to produce the most efficient product possible. One of the initial methods in Six Sigma is a fast diagram. This is a visual representation that identifies the needs and objectives our customer desires in a product to effectively produce a fully functional prototype. The structure of the diagram begins with a task followed by a basic function stemming in to secondary functions. By asking “How” in a rightward direction and “Why” in a leftward direction, a relevant flow will present itself informing us that the necessary criterion in place. Figure 1, shows the diagram we created in the beginning of the semester that provided a reference to us throughout the semester to help keep us on the correct path.

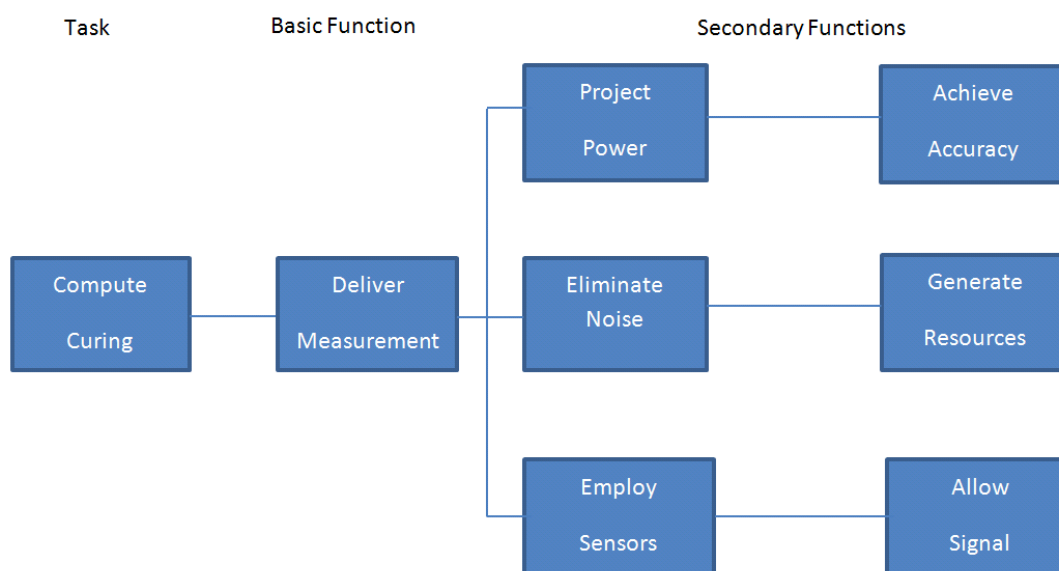


Figure 1: FAST Diagram

2.3 Critical Customer Requirements

Upon completion of the FAST diagram, we consulted with Texas Instruments (TI) to identify the critical stipulations that needed to be incorporated in our design process. TI stated that two of the most important requirements essential to our design were accuracy and low power consumption. Since our device will be immersed in concrete for the complete curing process, the batteries must last for at least three weeks. Delivering accurate measurements is also essential to our design in order for the customer to utilize the device. After prototype completion, TI intentions are to market this product. Isolating our customer's requirements gave us direction in what TI was looking for in a prototype. From the requests and selecting the desired components we created a House of Quality matrix. This diagram, as shown in Figure 2, portrays the correlation of customer wants and component capabilities that relays the optimal solution in our project. As previously mentioned, there are currently two other companies that have products similar to our design. We implemented their product amenities in the diagram in order to classify a way of being competitive. Presented horizontally, in the diagram, is each of the customer's requirements with a ranked value of importance. The vertical axis shows each of the components needed in the design and how each of them compares to the stipulations. The diagram on the right side gives a representation as to how we compare with the other two companies.

The configuration of the matrix displayed valuable information that was not previously discovered. The most enticing feature that our prototype offers, compared to other companies' products, is wireless communications between the monitoring system and the motherboard. The diagram showed how to meet customer priorities by exploiting the relevant parameters each component possesses. Three areas that TI specified and that the diagram showed, was producing an accurate prototype that consumed minimal amounts of power while maintaining enough range for communications.

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

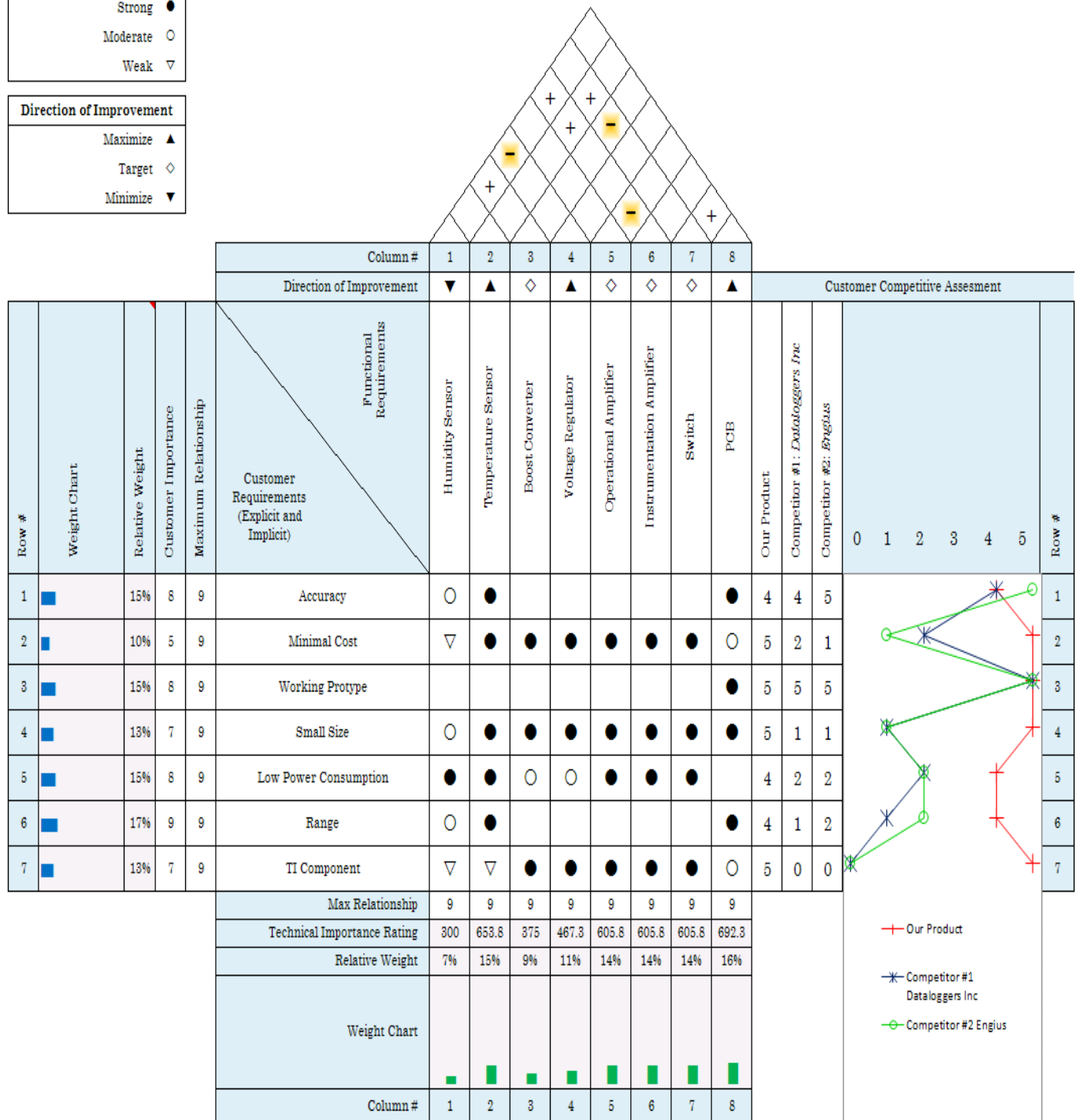


Figure 2: House of Quality diagram

2.4 Chosen Design Solution

Based off of the house of quality, we identified the most valuable property each component needed to retain. Sensors are the foundation of this prototype that requires meticulous attention in the selection process. We chose a resistance temperature detector (RTD) from TI, for being one of the most accurate form of sensing and its linearity in output voltage versus temperature over a very wide range. Linearity is a desired quality for reducing the complexity and the amount of circuitry needed in signal conditioning, which will ensure a minimal cost in production.

The humidity sensor followed the same principle as the temperature sensor in a manner of being effective as possible, while not demanding complex signal conditioning for functionality. Humidity devices possess in uncanny characteristic of requiring consistent calibration. For our application, a sensor needs to consume low amounts of power, and an absence of repeated calibration since it will remain in concrete. From our customer requirements, we concluded that a resistive based humidity sensor would be the most effective. No sensor can meet every requirement flawlessly, and these resistive sensors are more expensive than other forms.

To present relevant information to the microprocessor of the μ MAVRK, amplification and filtering is needed. These integrated circuits (IC) will need to meet proper accuracy and minimal power consumption requirements. Due to a steady decline in supply voltage from the power module (2 AAA batteries) being used, a voltage regulator will be employed. Before fabrication takes place, TI-TINA Spice simulator will test our conceptual design to ensure proper functionality. The overall design is to be broken up and tested in individual sections via prototyping. From there everything can be assembled and tested collaboratively. Results from each of these methods show the viability of a fully functioning module that will satisfy all of the customer requirements.

2.5 Budget

Design Team 5 was allocated \$500 from the College of Engineering. When initially meeting with Texas Instruments, they had stated they would supply additional funding if necessary. Once the team had created an initial design and began selecting components, the estimated cost was well below the allocated budget. Table 1 displays all the components affecting the initial cost estimate. DT5 wanted to create at least three PCBs in the event that prototype circuitry was ever damaged. All of the development tools were generously provided by Texas Instruments and were not taken into account for the initial cost.

Initial Cost Estimate		
Expense	Qty.	Price
40-pin Male Serial Adapter	3	\$12.50
Temperature Sensor	3	\$3.25
Humidity Sensor	3	\$96.30
Differential OP AMP	3	\$9.09
3 pin connector	6	\$3.03
Plastic Enclosure	3	\$4.15
Plastic Enclosure modification	1	Free(ECE SHOP)
Container	1	\$10(Estimate)
Heat Source	1	Free(Mech Lab)
Humidity source	1	Free
Material	1	\$5(Estimate)
PCB Fabrication Cost	3	\$150(estimate)
Total	29	\$293.32

Table 1: Initial Cost Estimate

2.6 Gantt Chart

The Gantt chart is an extremely useful tool that DT5 utilized in order to keep track of the overall project progress being made. The project was broken into subsections that were to be completed throughout the semester. With this tool, DT5 was able to visually see the critical path of events that needed to be accomplished. The resources section was used in order to delegate all technical tasks to each member on the team. Using this tool as intended, the team was able to stay on track throughout the whole semester. Figure 3 displays DT5's Gantt chart. For a larger view of the Gantt chart, refer to Appendix 3.

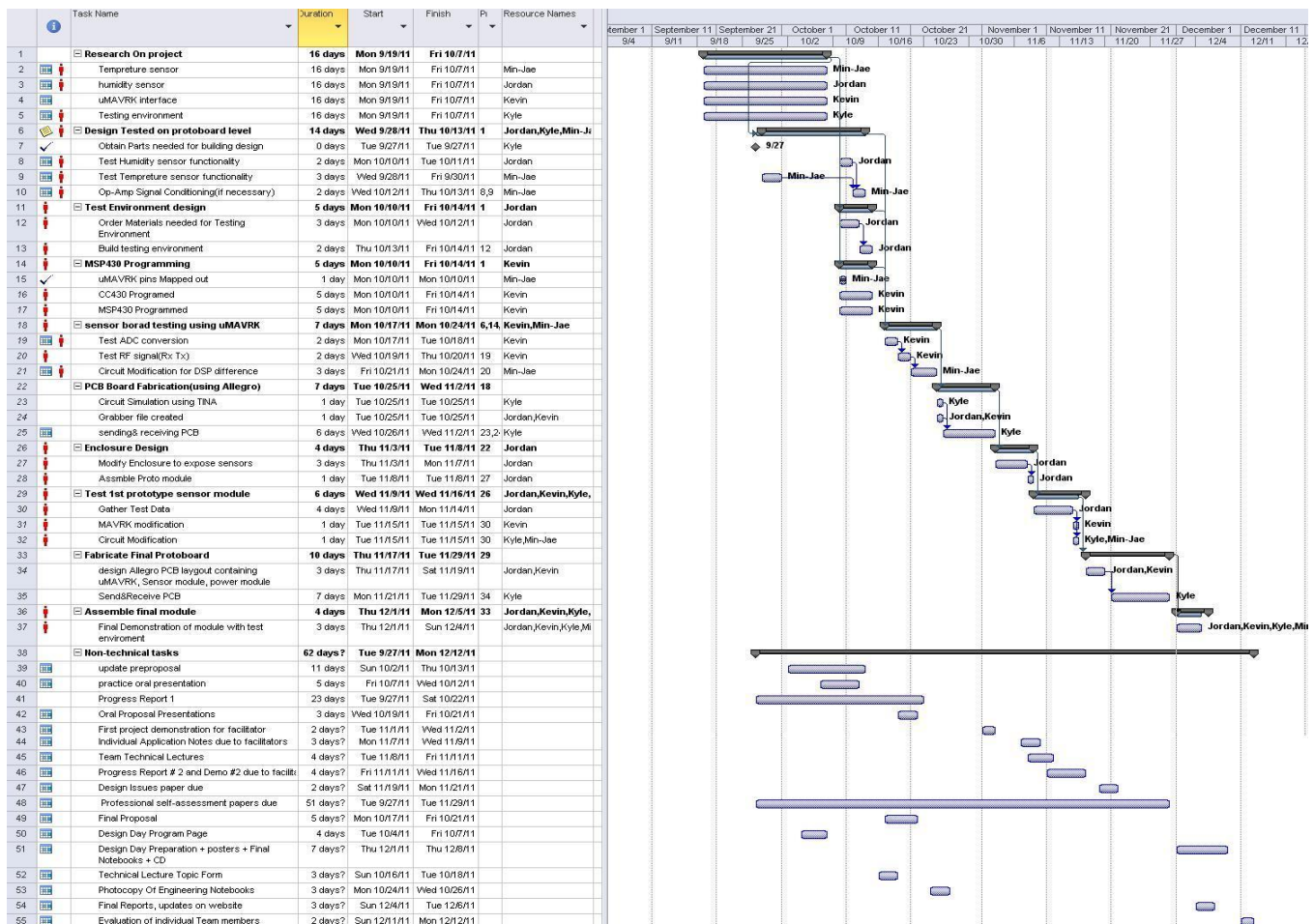


Figure 3: Gantt chart

Chapter 3: Technical Description of Work Performed

3.1 Conceptual Design Development

At the beginning of this project, our conceptual design of sensor module was having μ MAVRK as the center for gathering temperature and humidity data, with remote sensors equipped with RF circuitry that would transmit the data to the μ MAVRK. An assumption was made that each of μ MAVRK modules are too expensive and cannot be used extensively; therefore multiple remote sensors would communicate with one μ MAVRK, as shown in Figure 4.

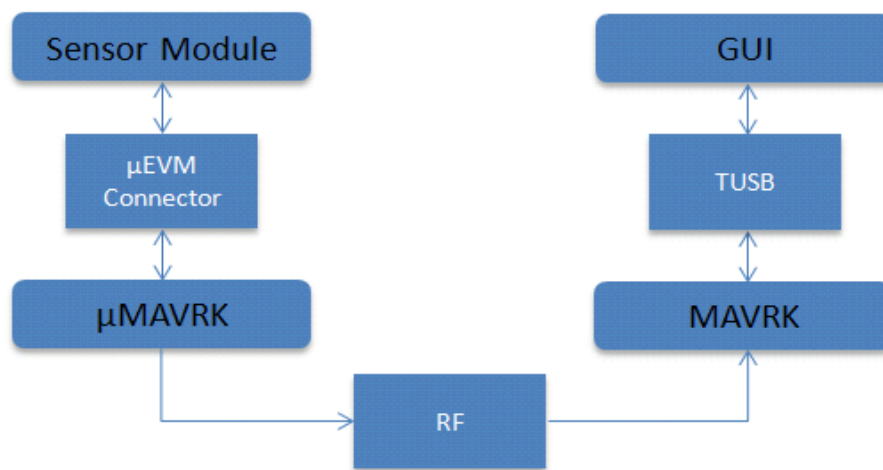


Figure 4: Initial conceptual diagram

However, from a customer interview we found out that the price of μ MAVRK was not a large factor for sensor module design, discouraging needs of remote sensors communicating with μ MAVRK. Our design goal was iterated to design a sensor module that will connect to the μ MAVRK via μ EVM connector. This port-pair connection is bidirectional. The sensor module relays humidity and temperature values, in analog form, to the μ MAVRK board, and this board turns the sensor board on and off every 15 minutes. This duration of time was chosen to ensure enough data is gathered in the GUI to interpret properly, while conserving enough power to transmit the necessary amount of information. The μ MAVRK will perform analog to digital conversion of the data from which it will be transmitted to the MAVRK through a radio frequency of 902-928MHz. For our application the MAVRK will send the received data to a GUI, personal computer, via TUSB cable. The MAVRK came programmed to interpret the information from the μ MAVRK. Code, derived from DT5, was implemented in the MSP430 of the μ MAVRK through a debugger module. Our design goal has been iterated to create a sensor

board in similar dimension as demo sensor board created by TI, improving accuracy, power efficiency, and performance. Designing procedure diverged into two segments – hardware and software, as shown in the functional block diagram below (Figure 5).

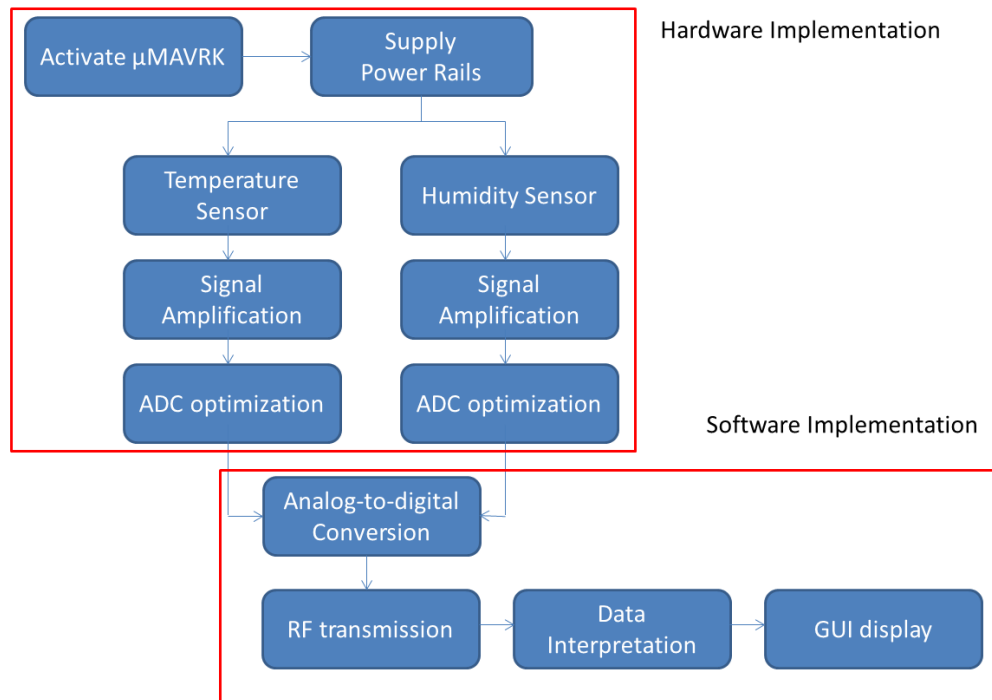


Figure 5: Final Conceptual Block diagram

3.2 Hardware Design Efforts

3.2.1 Pin Layouts

In the design process for the sensor board in compliance with μ MAVRK, a 40-pin analog interface DF40-40P-0.4V from Hirose Electronics is required in order for sensor board to communicate with the μ MAVRK. Each of the 40 pins is an analog interface that corresponds to pins on the CC430. However, due to its small dimension, testing analog circuitry is limited unless the board is populated. RF-UDEUG-MKV is a debugger module made to test circuit functionality on an analog level, mapping out pins on a 40 pin analog interface. Table 2 illustrates how each pin of interest on the CC430 is mapped out on a connector and debugger interface.

Pin Number	Mode of operation	Description	Connector interface	Debugger interface
14 ~ 21	P3.0 ~ 3.1	sensor power supply	11 ~ 18	J8 2 ~ 9
46	VeREF+	ref+ voltage for ADC converter	N/A	N/A
47	VeREF-	ref- voltage for ADC converter	N/A	N/A
22, 8, 41	DVCC	Power connections	N/A	N/A
1,2,3,48	P2.0 ~ 2.3	Analog signal channel for sensors	21,22,23,26	J4 2,3,4, 7
9	PM_UCB0CLK	SPI Clock signal	37	J2 6
5	PM_UCA0TXD	Digital data output(transmitted)	39	J2 9
6	PM_UCA0RXD	Digital data input(received)	40	J2 10
27,28,31,32	AVCC_RF	Radio Frequency Power supply	N/A	N/A
25	RF_XIN	Radio Frequency signal received	N/A	N/A
26	RF_XOUT	Radio Frequency signal transmitted	N/A	N/A

Table 2: CC430 Interface Layout

3.2.2 Temperature Sensor Selection

Temperature sensors come in three basic configurations of thermocouple, resistive temperature detector (RTD) and integrated circuitry (IC). The IC was not a fit for our particular application, because most of the IC type temperature sensors were optimized for measuring surface temperature rather than ambient temperatures. Thermocouples are ideal for measuring ambient temperatures, but require a reference temperature which we cannot provide since our final product will be submerged in concrete. This type of sensor outputs nonlinear relationships that need additional circuitry to compensate, as well. The style chosen for our design was the RTD, because it does not need a reference temperature and has relatively low drift and high accuracy compared to the other forms. The RTD sensor can be seen as a block of resistive material that is sensitive to temperature change. When there is a temperature change, a linearly correlated change in voltage is produced. Drawbacks of implementing RTD sensors, is that they have a slow response time due to thermal mass. However, this is not an issue because our end product is supposed to be operating for at least 3 weeks, sending data to the server once every 15 minutes.

PTS1206 from Vishay was selected as our RTD sensor because it is a very accurate device that possessed the desired size that made a good fit for our enclosure. If the dimension of component is too small, it can be hard to solder onto the exterior of the enclosure. The small change in resistance of 100 to 128 ohms for temperature range of 0 to 70°C made it necessary to include signal conditioning.

3.2.3 Humidity Sensor Selection

Humidity sensors are available in two different configurations, resistive and capacitive humidity sensor. For our design, resistive humidity sensor was selected due to its simplicity of implementation. Even though capacitive sensor has advantage of having linear output over full range of relative humidity with low response time, it required extensive Capacitance to Voltage converter which required two sets of oscillator and phase/frequency comparator. Moreover, the humidity range of interest in concrete curing does not require precise accuracy or full 100% Relative humidity. Humidity in concrete curing is important factor only in first 72 hours, verifying the relative humidity at the core of concrete being above 70% RH.

CGS-UGS from TDK was selected as our humidity sensor because it had relatively linear voltage output from 0.3 to 0.85V, 10mV increment for 1% RH. All the necessary circuitry was built-in, eliminating needs to apply control circuitry or calibration. The voltage supply requirement 5V was only drawback on implementation. To power up the sensor, TPS61222 was employed to supply 5V DC voltage.

3.2.4 Wheatstone Bridge Selection

Due to the fact that the RTD sensor changes its resistive value according to temperature, a circuit that can measure the resistive value of the RTD sensor is required. For our circuitry, a Wheatstone bridge configuration is implemented as shown in Figure 6. Wheatstone bridge is a circuit configuration that is used to find the resistive value of an unknown resistor when the values of the other three bridge resistor are known.

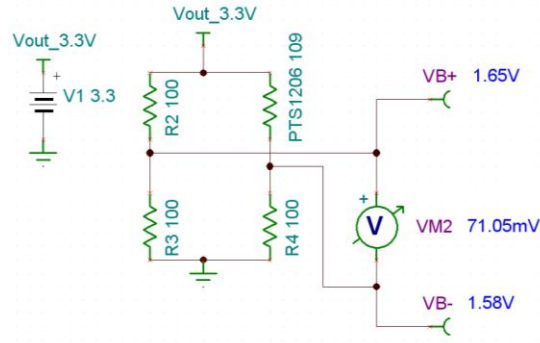


Figure 6: Wheatstone Bridge

The voltage between nodes, A and B, will vary according to change in the resistive value of the RTD sensor. We set all bridge resistors to 100Ω, giving V_B a range from 0 to 0.3V. To ensure the accuracy of our reading, two conditions must be met. Foremost, the three bridge resistors that make up the Wheatstone bridge should be precise to avoid severe implications. For instance, if resistor values are off by 1Ω from a 100Ω resistor, it will cause approximately $\pm 0.4^\circ\text{C}$ error in final reading. A constant, regulated input voltage is another mandatory factor. If V_{in} is not kept constant, the value of V_B can change without an influence of temperature.

Since our module is supplied by two AAA batteries the voltage, over time, will drop below the minimum level needed to maintain functionality. TPS61221, Low input Voltage Boost Converter was employed to supply a constant, regulated input voltage to the Wheatstone bridge, as shown in the Figure 7. It takes voltage input in range of 1.8V to 5.5V and outputs a fixed 3.3V. Due to unavailability of TINA simulations of TPS61221, the 3.3V power rail was not simulated via TINA but, external components were selected in reference to design created by SwitcherPro, a power management circuitry design tool created and distributed by Texas Instrument.

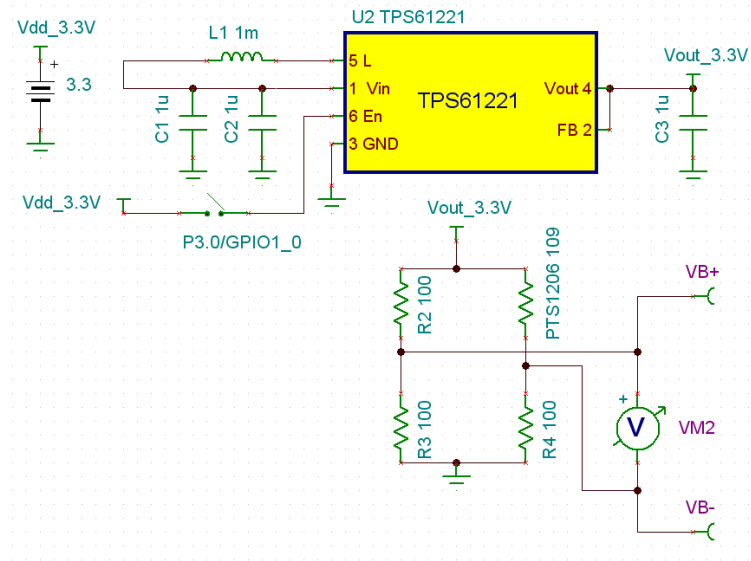


Figure 7: Wheatstone Bridge with Voltage Regulator

3.2.5 Signal Amplification

The maximum voltage for V_B , from the Wheatstone bridge, is 0.3V. This value is very low for the analog-to-digital converter (ADC) to make correct data conversion because; ambient noise voltages caused by different circuit elements are in range of 20mV. The internal voltage reference for ADC12-A, on the CC430, can be set up to 3.3V. If the maximum output of the Wheatstone bridge can be amplified to 3.3V it will ensure optimal resolution for ADC.

To amplify the difference between two nodes, two possible solutions are a differential amplifier or instrumentation amplifier. We chose an instrumentation amplifier, INA333, to reduce error that can be caused by amplifying noise voltage with V_B . To power up the instrumentation amplifier, we implemented the TPS61222, Low input Voltage Boost Converter. It performs identical operations as the TPS61221, except it outputs 5.0V as opposed to 3.3V. INA333 is configured to operate in single voltage supply which is all the batteries provide.

One drawback of using a single voltage supply is that we need to ensure common mode voltage (V_{cm}) of two input terminals of INA333 of at least 0.1V above ground. Adding a 100Ω resistor between ground and Wheatstone bridge ensures V_{cm} to be within range. To calculate the appropriate amplifier gain, MATLAB was utilized.

```

syms y x temp T;
Rg = 5.23*103;
Gain = (1 + 100*103/Rg); % gain defined by value of Rg
Vout = 3.3;
Vin = 3.3;
A = 3.9083*10-3;
B = -5.775*10-7; % constant A & B given by datasheet of PTS1206
y = Gain * (0.5-100/(100+x)) * (Vin-100/(100+200*(x+100)/(300+x))) -Vout;
% RTD resistant calculation
b = double(solve(y));
temp = 100 * (1 + A * T + B*T2) - b(1); %Temperature calculation
result = double(solve(temp));
b(1) % resistance of RTD sensor
result(1) % corresponding temperature

```

R_g was varied until we got a calculated temperature of 70°C at the output of 3.3V. As a result, we assigned our gains to a factor of 20.12 that is shown in Figure 9.

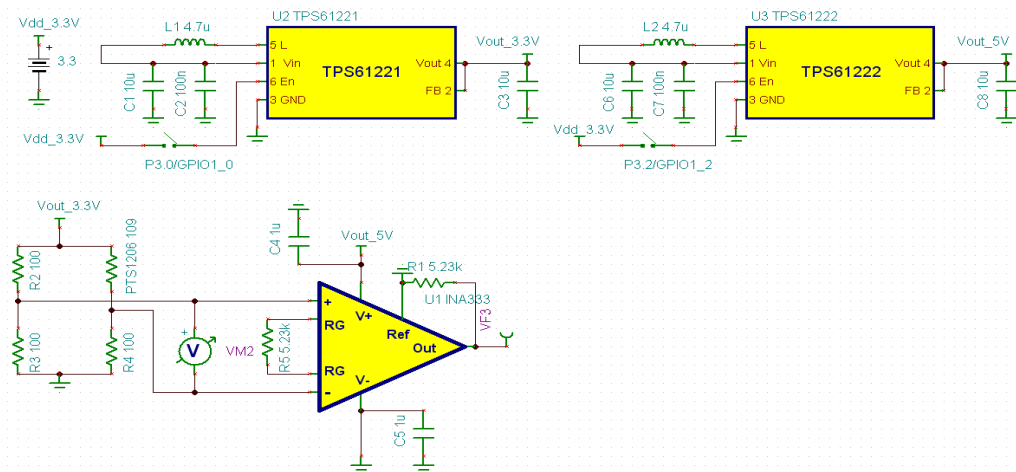


Figure 8: RTD sensor Wheatstone bridge with amplification factor of 20.12

3.2.6 Enclosure

A watertight, plastic enclosure was selected to protect the circuitry while submerged in concrete. The enclosure is composed of acrylonitrile butadiene styrene (ABS) plastic to minimize signal attenuation in communications. Dimensions of 4.7" by 2.6" by 1.6" were selected from the size of the μ MAVRK, power module and sensor module connected together. Two holes were drilled on the top surface to allow the humidity and temperature sensors to be exposed to the concrete. To seal any gaps between the sensors and the enclosure, silicon was applied. Silicon also provided the necessary rigidity to hold the sensors in place.

3.2.7 C-SAR-ADC Optimization

Successive Approximation ADC operates by using a comparator. When an input voltage is supplied into a converter it is compared with a mid-value reference voltage, and the most significant bit (MSB) is flagged to high if V_{in} is higher, and 0 if V_{in} is lower. Input voltage is then compared with V_{ref} over $2 \pm V_{ref}$ over four depending on if the MSB is high or low. Sequence continues until the least significant bit (LSB) is flagged high or low, giving binary combination of numbers.

In the case of C-SAR ADC, the ADC conversion is driven by two switches as shown in Figure 10a. Initially S1 is low and S2 is high and when analog-to-digital conversion occurs, S1 is set to high and S2 to low. C_{sh} is charged up to voltage input and when switch returns to original state, voltage on C_{sh} is compared with V_{ref} to be converted into digital data. However, when ADC operates in high frequency, there can be a case where S1 set to high, before C_{sh} discharges, creating a feedback and altering the voltage input. To avoid such errors, external RC circuitry and buffer amplifier is required (Figure 9). For our circuitry, we have chosen OPA363 as our buffer amplifier, based on application note provided by manufacturer.

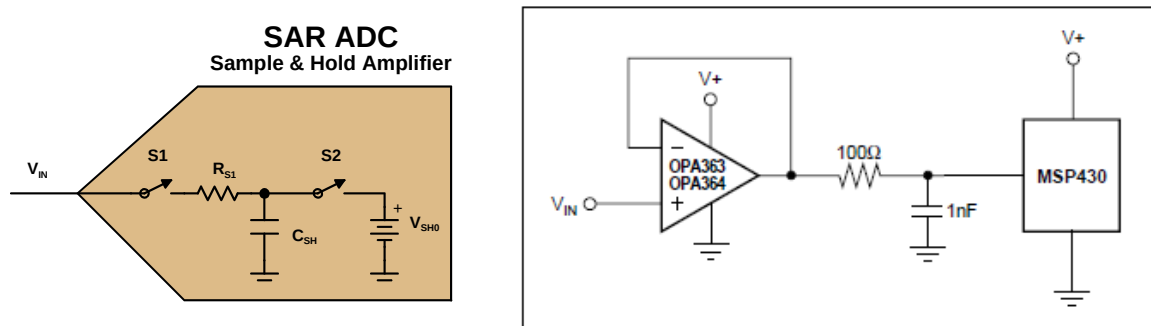


Figure 9: a) simplified topology CSAR ADC converter b) RC filter with buffer amplifier

The value of the RC filter has been altered to accommodate difference in sampling rates of AD converter in MSP430. Buffer amplifier for humidity sensor has been configured to have gain of 3 to reach maximum resolution for ADC, the schematic shown below.

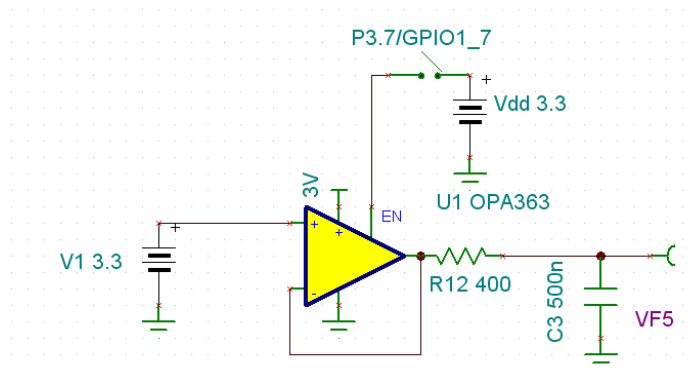


Figure 10: ADC signal conditioning circuitry

3.2.8 Power Optimization

To eliminate idle current drawn, TS5A3166 a voltage controlled switch, is implemented at the voltage supply of the Wheatstone bridge. Enable pins of TPS61222, TPS61221 and two OPA363 has been connected to GPIO pins of the μ MAVRK to be sequentially powered up and down. Details on timing sequence of components are covered in software development section of this chapter.

3.2.9 Final Schematic

The final schematic of circuit is shown in Appendix III. Sensor board circuitry will be powered directly from a battery source in range of 2.8V to 3.3V. Voltage from the battery will then be boosted and regulated via two DC-DC voltage boosters, creating a constant 3.3V and 5V rail. The resulting analog output at the end of circuitry will be in range of 0.5V to 3V, serving as inputs to a built-in 12 bit ADC converter on the CC430.

3.2.10 Simulation and Prototyping

Due to limitation in size of component, most of the testing on circuit functionality was unable to be conducted before population of sensor board. However, Tests on functionality of temperature and humidity sensor were done by implementing LM741 general purpose operation amplifier. Step-up DC to DC booster has also been tested using DIP adapter. All the other circuit components were simulated via TINA, a PSPICE based simulation tool. Refer to Appendix III for TINA simulation results.

3.2.11 Design Iterations

- i. 5V DC-DC step up booster was replaces from TPS60241 to TPS61222. TPS60241 had current output limitation of 1.5mA, insufficient to power up both INA333 and Humidity sensor.
- ii. Operation amplifier for detecting and amplifying bridge voltage of Wheatstone bridge was replaced from LM741 to INA333 due to dual voltage supply requirements and high noise voltage on LM741.
- iii. RTD sensor was replaced from PTS100 to PTS1206 for bigger dimension.
- iv. 3-pin jumper connector was added to 3V voltage rail to control voltage supplied to sensor board when board is not in operation.
- v. From populated board, 100 Ω resistor across V_{out} of Humidity sensor and ground was removed. 10uF capacitor was added instead. A100 Ω resistor was populated by error on schematic.
- vi. From populated board, R14 and C16 was swapped place. Error was cause during population process.

3.3 PCB Design and Fabrication

Due to the abstract application of this project, circuit components needed to be carefully selected. Once we had an idea of how we would create the circuit, the team searched for the exact components that would satisfy design requirements. Texas Instruments' TINA simulation was utilized in order to verify our selection was justifiable. It was proposed originally to fabricate multiple boards early in the semester in order to verify our design was error free. Due to the complexities in circuit design DT5 was unable to populate the first revision board by the deadline needed. The team focused on the circuit design extensively to ensure there were no errors in design. For this reason we were able to fabricate one final product with complete functionality and accuracy.

3.3.1 PCB Design

The PCBs were designed using Cadence's Allegro PCB Designer Software, a useful tool with many applications. Initially the team began creating the PCBs with Dip Trace[], which is also a very useful software package. Creating the PCB, regardless of software package was implemented, needed time allocated in the schedule in order to learn the software and process. Time management is a large portion of any design process and due to the smaller learning curve, Dip Trace was originally chosen. Although useful, Dip Trace did have some limitations. Texas Instruments will eventually incorporate our design into their product portfolio, and because of this all files must be compatible with their software. Dip Trace's schematic and PCB files were not compatible with Allegro files, which was the motivation for DT5 to switch to Allegro. Within this software, there are two schematic creators, Design Entry CIS and Design Entry HDL. Initially, HDL was the software package being implemented and consumed an extensive amount of time. After discussing some design issues with TI, recommendations were made to utilize CIS instead because of a less steep learning curve. Switching to Allegro CIS was found to be extremely beneficial for both DT5 and TI. The schematic and PCB files were finally in the same format as TI's designs. DT5 was able to utilize TI's component library for all schematic design procedures. This eliminated the time that it would have taken to create each individual component footprint.

After the schematic design was complete, DT5 moved onto the PCB design. During this point in the project, TI provided a set of PCB template files. These files were useful because once again, DT5 only needed to concentrate on populating the board correctly while eliminating the time needed for creating initial board set up. Initial board set up would not take long if the board was only a top and bottom layer, but DT5's PCB was a four layer board. Layer one was the top of the board where all the surface mount components were placed, layer two was the ground signal, layer 3 was the testing signal layer, and layer four was the bottom of the

board, where the sensor module can connect to the debugger interface. The ground plane is not necessary, but provides useful functionality since it eliminates the need to route each device to ground.

Although the tools provided by TI did help reduce time, the PCB design process still required a significant amount of time to complete. For a more detailed description on how the printed circuit boards were created, documentation can be found on DT5's website in the application note section.

3.3.2 Fabrication

Due to the complexity of the design, number of boards requested and size of the boards, the fabrication cost was well beyond DT5's budget. Texas Instruments graciously processed the Fabrication order and covered the cost. After the fabricated boards were complete, TI also professionally soldered all components except our sensors. With this assistance, DT5 eliminated \$1,434 from their costs.

3.4 Software Interface Design Requirements

The designed sensor board sends temperature and humidity values to the μ MAVRK in a range of 0V to 3.3V. Code is implemented in the μ MAVRK's microcontroller for interpretation of the voltages. Software design incorporated three different applications running on three different devices, shown in Figure 11.

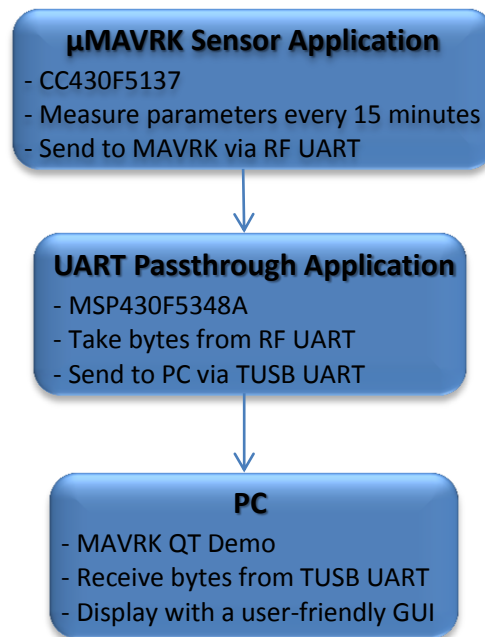


Figure 11: Software Flowchart

The first stage, the signal conditioning circuit (SCC) is attached to the CC430 with software running on the CC430 that will sample (every 15 minutes) the output of the SCC. In addition to sampling; it will turn on the microprocessor, send out enables attached to our circuitry, sample analog value, apply mathematical equations to make sense of these values, and send these bytes over the RF UART to the MSP. The UART application takes place in the MSP430. It receives the RF UART bytes and sends it over USB to the PC. The PC will be running QT application designed for receiving the bytes, and -friendly GUI for viewing the data.

3.4.1 Software Design Strategy

We attempted several design iterations in order to obtain a fully functional program. In the first design iteration, our goal was to use TI's signal condition circuit and their software elements to produce the results that we are hoping our design will achieve. The products we received were still in the developmental stages, which meant that online guides for setting up their product and running their temperature and humidity sensing applications were prematurely written. Refer to section 3.5, for an evaluation of Texas Instrument's μ MAVRK/MAVRK tools. Ultimately, we finished this step, and proved that our goals were achievable. Also, in observing the use of their board and software, we noticed that there were several things we could do to improve on their design.

The second iteration took place once we proved that their software was written correctly, from which we began modifying it for our purposes. At the end of this iteration, it became possible to accept the analog values into the μ MAVRK, and see these values being displayed on our QT application. This led to a working prototype however; there was no analog value present on the GUI.

In an attempt to implement this formulation, alterations of the original code was needed to be compatible with our hardware interface. This code now contained orders to search for an I2C interaction in an attempt to locate a passive interaction. I2C is one way that the MCU can receive data bits from its peripherals. This was implemented in the original code. There is a direct connection between the MCU and the temperature sensor. This direct connection makes it possible for the MCU to address the sensor directly, and receive the bits on the SDA line. This is all synchronized with a clock and is shown below.

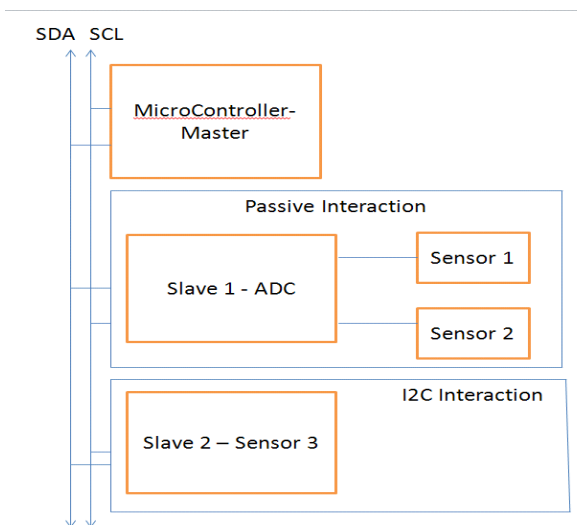


Figure 12: Software Connectivity

In the passive method of data acquisition, the team wanted to wire the circuit's output to a GPIO pin. The microprocessor will do a sweep of all interested input pins to look for analog signals. Once found, these values will be passed through an ADC and in to the MCU for further processing. When the code was changed to fit this method, it became possible to attach our own hardware to the μ MAVRK and see the analog voltage on our GUI running in the PC. Our circuit board still required enable bits (invoked by our software) to activate its switches, that led to the next iteration.

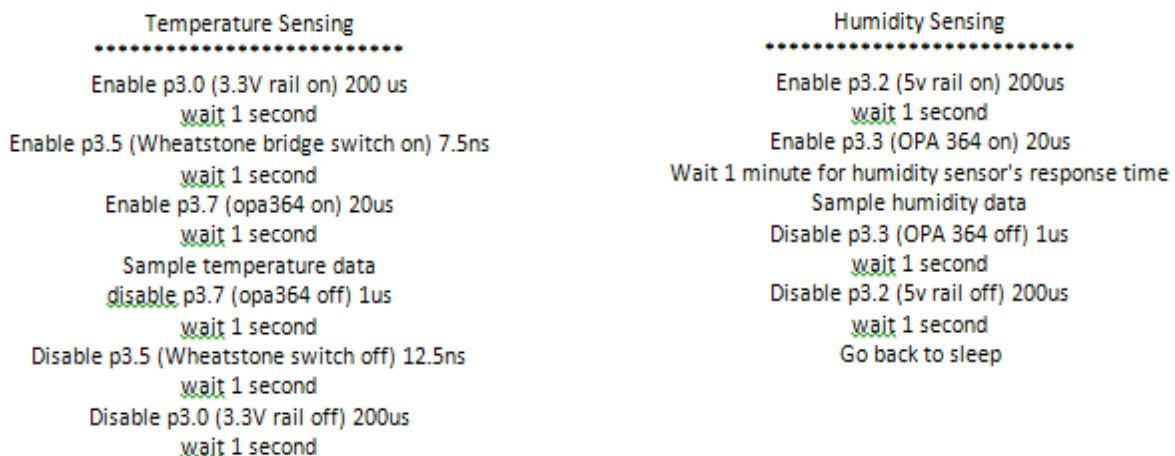
In this situation, enable bits were relayed to the correct ports. Mathematical equations were applied to the code to find the temperature and humidity values. To find temperature, given its voltage output, Matlab was used to solve for the correlating temperature that was used in an algorithm in the code. Refer to Appendix 3 for the code. Our embedded device only handles 16 bit numbers, while the `sqrt()` function, commonly utilized in C code, returns a 32 bit number. This made it possible for design demonstrations.

3.4.2 Final Software Design

Based off the previous improvements, addition code was written for prolonging battery life. For demonstration purposes, we want to have the device constantly working to show that it works. However, in actual application of this software, we need to turn on the device once every 15 minutes for power consumption. Verifying functionality with the enabling circuitry allowed the board to switch on and off, which provided power conservation. The switches close sequentially, which results in sections of the board to turn on, sample and relay information, then turn off. This sequence of orders is shown in the following timing diagram.

Timing Diagram

Sleep - 15 minutes
Interrupt



3.5 Evaluation of Texas Instruments' MAVRK Starter Kit

Texas Instruments requested a report about the MAVRK starter kit, which documents the issues and complications encountered throughout the semester. Here, we will describe problems encountered and the steps taken to resolve the issue.

Setting up the kit was fairly trivial, largely due to thoroughly labeled parts. Tutorials online were very informative and meticulous. The steps taken to run the kit where:

1. First, we had to set up a software repository to receive the pre-written modules. Setting up this connection is the only way to receive their updates, as their code is not in a final-release form. There were several installations such as TortoiseGit, Msysgit, and Putty. This process is outlined in this tutorial:
http://processors.wiki.ti.com/index.php/MAVRK_Software_Installation_Guide
2. In choosing the IDE, we ran into some problems. First, we decided to use the IAR Workbench. This was one of the options outlined in the tutorial. However, the user cannot use this software as it is currently. The free version given to us in CD is limited to only 8K. The modules will need much more than that. Next, we used Code Composer 4 (also given to us on CD). This also cannot be used. We get strange build errors. The version that can work with the MAVRK is **Code Composer 5**. This can be downloaded from TI's website without waiting for approval. Just make an account and proceed.
3. We cloned the modules into our repository. No problems here.
4. The next thing we did was to build and run the MCU application (UART Pass-through). This built and debugged fine.
5. We built the Sensor Demo Application on the μ MAVRK fine. However, upon Debugging, we get the following error: "The target setup (MSP430F5438A) does not match the actual target type (CC3430F5137)".
6. TI notified us that the online guides for setting up temperature sensing and humidity sensing were incorrect. In the new guide, the team was able to correct the problems from step 5.

Chapter 4: Test Data with Proof of Functional Design

4.1 Baseline Reference

Given the abnormal environment of concrete the circuit will be exposed to, we needed to create and verify an alternate substance that mimicked properties of concrete that allowed us to remove our prototype to make any necessary adjustments. After consultation with numerous civil engineers and concrete specialists we derived an accurate substitute. The composition consisted of 15% clay and 85% sand. Clay imitated the thick, cement paste that is used to adhere and harden materials together. Sand represented the fine aggregate and course aggregate that is utilized in the hydration (curing) process for the basis of strength. The percentages are based on the Department of Transportation's procedure of, "Concrete Manual: Mix Design." Concrete produces an exothermic reaction, in the form of heat, during the hydration process, and though sand and clay alone do not create this additional form heat it is the closest composition to concrete without creating any adhesion.

To test the prototype in both cold and warm temperatures, a source for both would be needed. A hot plate was purchased with temperatures varying from 20°C to 130°C in increments of 5°C. For cold temperatures, each sand and clay sample was placed in a freezer until the temperature dropped below 0°C. Since temperatures below freezing are not plausible for concrete to cure, tests were recorded from 0°C on up. As a reference for temperature, other than standard gauges, the Amprobe THWD-1 meter was used for comparison. This meter is accurate within 1°C.

4.2 Humidity calibration

The humidity sensor we chose to use in this project possessed $\pm 5\%$ accuracy in relative humidity (RH) measurements from 0-95% RH. The output voltage ranged from 0-1V, giving a correlation of .1V to 1% RH. Verification was required to see that the humidity sensor would produce these results. Two different tests were performed to ensure accuracy.

4.2.1 Relative Humidity Calibration Test One

Omega Engineering Inc. manufactures a calibration kit for humidity sensors using saturated salt solutions. The validity of this test is shown in the ASTM standard E104-85 that is accurate from temperature ranges from 0°C to 50°C. To produce 11.3% RH, fill the 50mm bottle with 28 grams of “LiCl 11.3%,” and add distilled water in the container, stirring after each addition, until the salt can absorb no more water. Table 3 shows the results of three tested humidity sensors that contribute to the accuracy authentication.

CHS-UGS Humidity Sensor	V _{out}	RH (%)	Percentage Error (%)
1	0.10981	10.981	-2.82
2	0.11735	11.735	3.85
3	0.11652	11.652	3.12

Table 3: LiCl Humidity Test of 11.3% RH

The next part of the experiment is to mix another salt solution to produce 75.3% RH. This involves adding 34 grams of “NaCl 75.3%” in to another 50mm bottle with distilled water until the salt is completely saturated. Results from this experiment are shown in the Table 4.

CHS-UGS Humidity Sensor	V _{out}	RH (%)	Percentage Error (%)
1	0.75365	75.365	0.086
2	0.74986	74.986	-0.417
3	0.75032	75.032	-0.356

Table 4: NaCl Humidity Test of 75.3% RH

The ASTM standard proclaims 100% accuracy at room temperature (25°C) in which the experiments were conducted in. The Fluke 8840A Multimeter was used to show the output voltage of the humidity sensors. The accuracy of V_{DC} for this machine is up to 0.0025%, which still keeps the humidity readings within $\pm 5\%$.

4.2.2 Relative Humidity Calibration Test Two

The next calibration experiment involved calculating humidity based off mass ratios. By dividing the mass of added water by the mass of completely dry sand and clay we were able to calculate the exact humidity percentage present in each sample. Figure 13, shows the setup of how humidity sensors were tested in varying relative humidity. Ten samples were made with 100grams of soil, and each of them had different theoretical humidity levels. The results of each of the three sensors at 10 different relative humidity levels are shown in Figure 14.

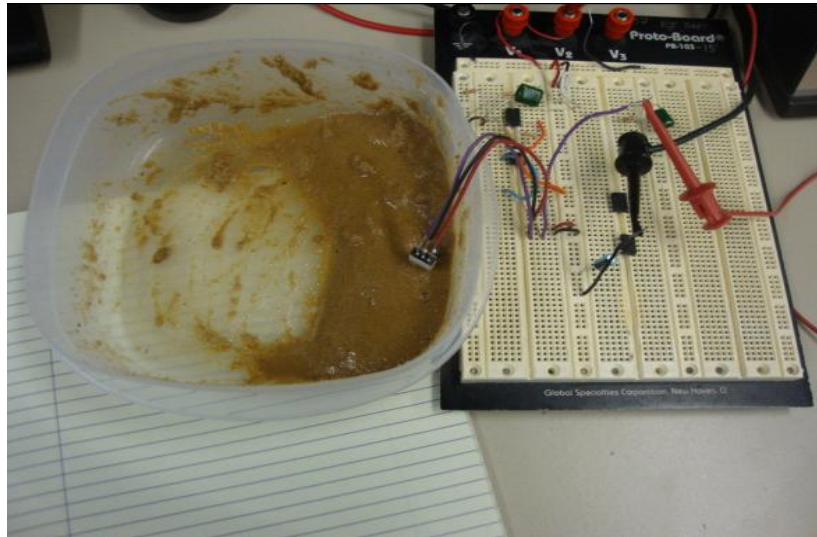


Figure 13: Testing Environment

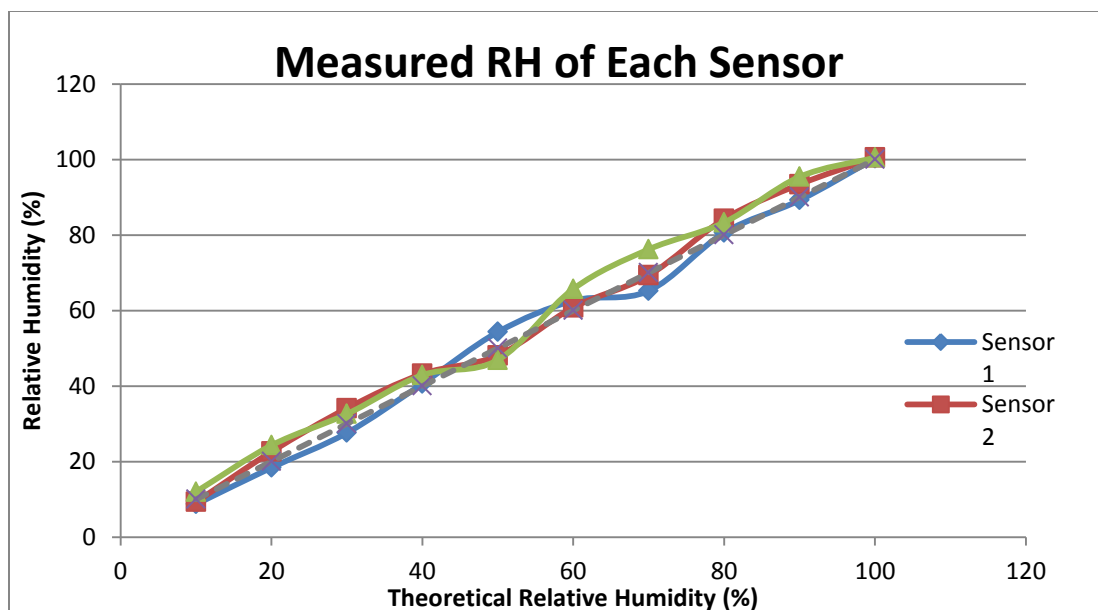


Figure 14: RH of the 3 CHS-UGS sensors

4.3 PCB Troubleshooting

Once DT5 received the fabricated PCB, testing began immediately. This was done to make sure there was no error on our part and to see if the fabrication manufacturer caused any errors. When the μ MAVRK and sensor module were connected to the MAVRK via the RF Debugger, no data was being received from the sensor module. To isolate the problem, each component was separated and tested. The sensor module was designed with three jumper pins in place for testing and troubleshooting purposes. To verify all circuit components were populated correctly, DT5 supplied 3.3V to the source, tested the output for all components on board. Output voltage was tested at C7 of the TPS61221DCK IC with results showing 0V. This result verified that the problem was not the circuitry itself but a bad IC.

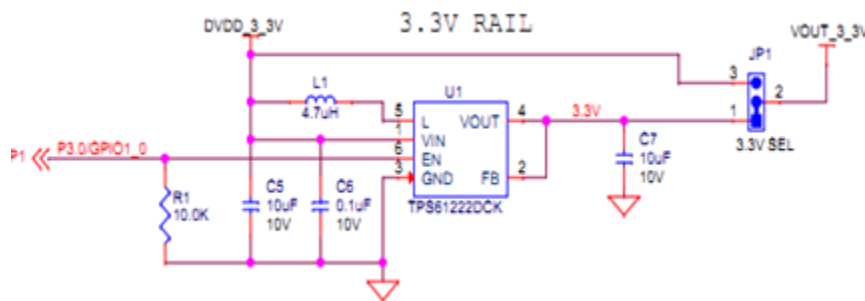


Figure 15: Voltage Regulator (3.3V Rail)

DT5 resolved this issue temporarily by bypassing the TPS61221DCK completely, then supplying source voltage directly at the Wheatstone bridge input, until a new component was ordered and installed. The 3.3V rail is in place because the circuit is being supplied by a battery source, which reduces in voltage over time. In order to relay an accurate temperature, the voltage must stay above 2.8 V. For demonstration purposes, DT5 tested and verified that the circuit is producing the correct output voltages with a brand new battery source.

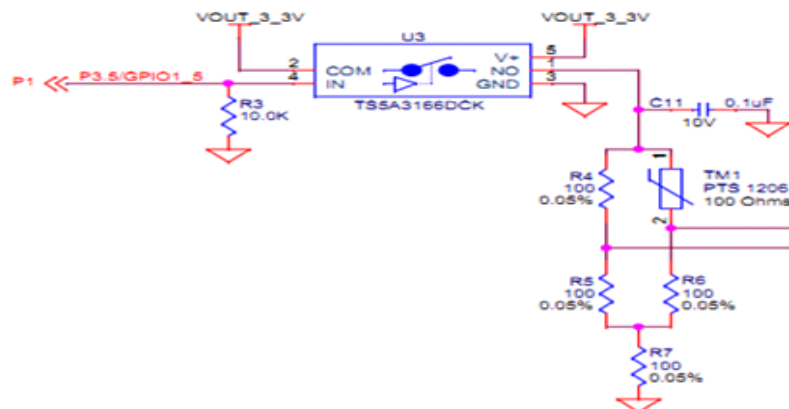


Figure 16: Temperature Sensor sub circuitry

4.4 PCB Testing

Due to the time constraint DT5 was faced with, PCB fabrication was extremely detailed, insuring we had a working circuit board. This portion of the project was the most time consuming. The team was able to thoroughly test the PCB, verifying functionality of all the IC components and their connectivity, except for the TPS61221DCK 3.3V Rail. When a voltage was applied, the component drew one amp. In diagnosing the problem, no short circuiting was found which led to the conclusion that the IC component was faulty. Without the 3.3V rail the sensor module can still be used as intended for demonstration purposes, by ensuring that the AAA batteries are supplying at least 2.8V, and replacing them when they drop below the limit. As a result, the temperature reading will not lose accuracy. Without complete software, DT5 utilized the external jumper pins, already present on the board, for powering and testing the circuitry.

When testing the TPS61222DCK 5V rail, a supply voltage of 3.3V was delivered to the external JPIO, representing V_{dd} , while another 3.3V power supply was applied to enable the IC switch. Using the 34401A multimeter, the output voltage of the 5V rail was measured at component C10 (reference schematic) to be 4.9V, which is in the acceptable range.



Figure 17: 5V Rail Output Voltage

To measure the output of the temperature sensor, one person externally enabled the 5V Rail, while another externally applied 3.3V to the Wheatstone bridge, and then using the multimeter, measured the output of the INA333 at pin 6. An acceptable 1.5V resulted, as shown in Figure 18.

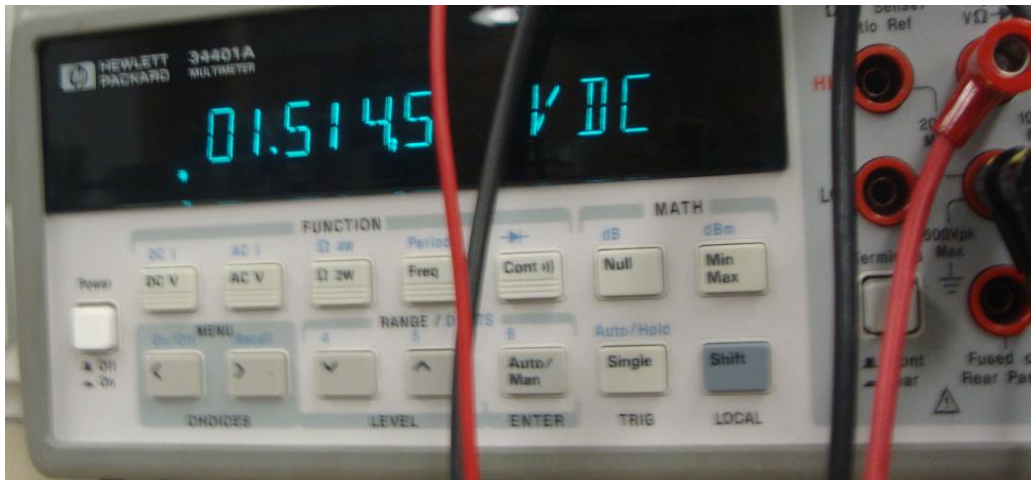


Figure 18: Temperature Circuit Output

In testing for proper functionality of multiple humidity sensors, leads were first soldered to each humidity sensor and connected to the PCB individually. The CHS-UGS has a linear output range of 0-1V with a supply voltage of 5V. See to section 4.2 for testing procedures. Figure 20, shows the output voltage from a single humidity sensor when submerged in soil composition containing 40% RH. An output voltage of 0.37V was measured, corresponding to 37%RH. Along with the mass calculated humidity, the Amprobe THWD-1 ($\pm 1\%$ RH error) showed a reading of 39.7%RH. From both of these tests, this particular humidity sensor was deduced serviceable.

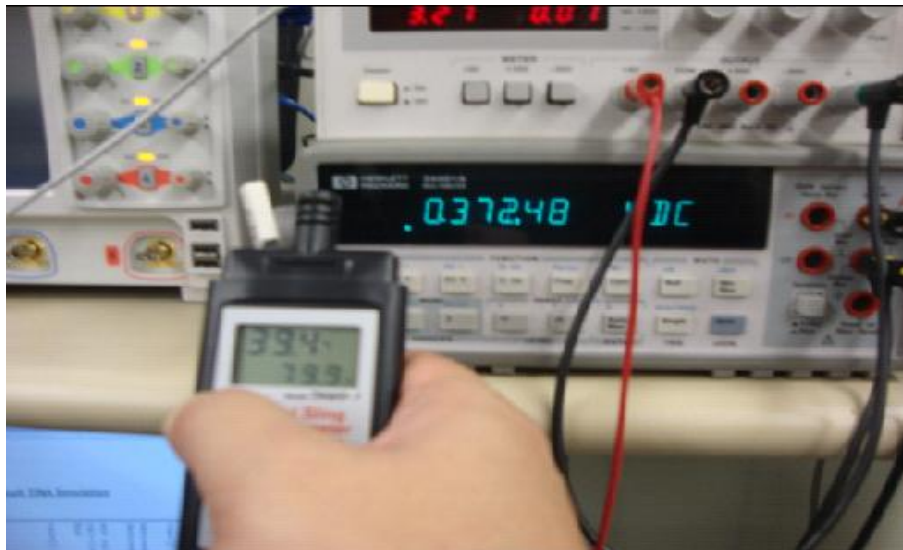


Figure 19: Humidity Sensor Circuit Output

As a result of the challenges that DT5 were faced with when it came to programming, the team was unable to implement their testing procedure, of immersing the device in a concrete alternative. DT5 was able to verify that the circuitry of this project was operating as expected. After completing the circuitry testing, DT5 was very pleased with their results due to the accuracy in the information gathered. Testing results verified that DT5 was able to properly condition the humidity and temperature signals, followed by sending the signals to an desired destination.

Chapter 5: Final Cost, Schedule and Conclusion

5.1 Cost

Over the course of this project, Design Team 5 was able to stay within the 500 dollar budget given to them by the College of Engineering. With the help and generosity of Texas Instruments, the team was able to eliminate the cost of PCB fabrication from their budget completely. Texas Instruments also provided the MAVRK starter kit, which was essential to the development and completion of the project. Figure 20 displays the final product cost per unit. Figure 21 displays the cost that DT5 would have endured if Texas Instruments had not sponsored out team.

Misc. Circuit Components	\$11.02
Device Enclosure	\$4.19
Temp Sensor	\$3.61
Humidity Sensor	\$32.31
MAVRK Starter Kit	Provided by TI
uMAVRK RF Module	Provided by TI
uMAVRK Power Module	Provided by TI
Hot Plate	\$17.99
Metal testing Enclosure	\$13.99
Digital Thermometer	\$14.99
Fabrication	Provided by TI
Total	\$106.63

Figure 20: Final Project Cost

Device Enclosure	\$4.19
Temp Sensor	\$3.61
Humidity Sensor	\$32.31
MAVRK Starter Kit	\$199.00
Hot Plate	\$17.99
Metal testing Enclosure	\$13.99
Digital Thermometer	\$14.99
Fabrication	\$1,435
Total	\$1,731.94

Figure 21: Cost without TI Contributions

5.2 Schedule

Design Team 5 was able to stay on schedule for the majority of the project. Time management and project management are two complex yet essential skill sets needed for successful completion of any project. DT5 was able to stay on schedule by utilizing Gantt chart created early on in the semester. Although DT5 frequently compared overall progress to the Gantt chart, weekly goals and objectives were also established. These weekly goals sometimes would not have a large enough impact to be included on the Gantt chart, but rather a supplement to those tasks ensuring successful completion. Many tasks were allocated a shorter duration of time in order to achieve an earlier completion date. With this scheduling method implemented, there would be additional time at the end of the semester in case the project drifted off the critical path. DT5 initially intended to fabricate multiple PCBs during the semester, but due to the design issues that occurred were only able to fabricate one PCB. The way in which the project was scheduled, this did not take the team off schedule. The Gantt chart used for this project can be found in *Appendix 3*.

5.3 Conclusion

Design Team 5 successfully designed, tested and verified functionality of the sensor module of our wireless sensing system for concrete curing. An effective baseline testing environment was also designed, which eliminated the need to test our device in actual cement. Due to time constraints that faced DT5, the software for our wireless sensing system was unable to be implemented. Software issues restricting our completion largely included the incompatibility between sensor modules. Much of the software efforts attempted to resolve the interface incompatibility. Without the proper software the team was unable to utilize the testing environment created to reference concrete. However, both the testing environment and sensor module proved to function properly. While not every customer stipulation was satisfied, the completed prototype met all criteria except displaying proper information on a GUI. Much time was spent on the design and PCB fabrication in order to guarantee customer satisfaction. Each signal output that would have been read by the computer GPIO was tested and verified that they were functioning as expected.

In terms of completion, the sensor board designed and fabricated by DT5 has been verified to produce desired outputs, with temperature readings within $\pm 3^{\circ}\text{C}$ tolerance, compared to readings of digital thermometer. For Humidity sensor reading, sensor circuitry had verified functionality of humidity sensor in ambient environment, but failed to achieve accurate data in concrete simulated environment at levels close to the solubility limit (100%), due to polarization of sensor accumulating moisture when submerged. In addition, DT5 was able to implement enclosure for sensor board circuitry with water proof plastic enclosure. A more compact enclosure could have been implemented by utilizing the μMAVRK power module instead of the AAA battery pack. Final Cost of the Project per unit was \$106. Many of the components are Texas Instruments products, which helped tremendously in reducing final costs. This value does not include the PCB fabrication in which Texas Instruments graciously provided us with, which was a savings of over \$1,400. Once this device is implemented into mass production, cost would substantially decrease.

DT5 was able to stay on schedule for the majority of the project duration. Minor challenges during the end of the semester had altered the schedule's critical path. When tasks started to go off track, many team members worked long nights in the engineering building, strictly focusing on the project in order to get the team back on schedule. Experiences such as this and many other real world design issues this semester have given the team valuable experience. Each issue presented was thoroughly analyzed and systematically resolved. The members worked together in such ways that produced results, resolved problems and taught everyone important aspects of the engineering industry. For these reasons, design team 5 did have success in their project.

Appendix 1: Team Members: Roles and Responsibilities

A.1.1 Kevin Yeh



Kevin's responsibilities were primarily software. During the installation and configuring process, he was the main point of contact between the team and TI for debugging issues. Once these issues were resolved, he worked on learning technical details involved with hardware-software interfacing.

During the hardware design phase, Kevin took part in providing support to Kyle for learning Allegro PCB Design and using it to construct the sensor board. Later, Kevin was mainly in charge of implementing the correct software features that will put the team's hardware to full use. He utilized a variety of online research; Texas Instrument's help, and sample code to develop one of three important software applications used in the system data flow.

Lastly, Texas Instrument has requested that the team submit a report evaluating the μ MAVRK's ease of use. Since Kevin took the lead in resolving system issues, he also became responsible for submitting a report on the problems he encountered, viable solutions to these problems, and suggestions on how to improve the overall experience of buying this product.

A.1.2 Kyle Schultz



Kyle led the team through the printed circuit board fabrication process. There are many PCB design software packages available, all varying in difficulty. Since our design will one day be produced by TI, all schematic and PCB files must be compatible with TI's software. As a result, there was no choice in software selection. Kyle learned the Cadence Allegro Software package in order to create our complete prototype in schematic format.

From there, he was able to incorporate additional attributes to each component and map them to the PCB files. He had to strategically place each component on the board to insure the best functionality. Due to the time constraint design team 5 was faced with, he had to make critical decisions ensuring no error in board design.

Kyle played a large role in circuit component selection and implementation. Once design specifications were established, he had to implement specific components to deliver those results. To do this, he performed many of the initial TINA simulations and compared them to the component data specifications. Once the two were equal in characteristics, the simulated components were then purchased for actual physical testing.

Kyle also was involved in circuit modification efforts throughout the semester. Whenever testing results in a need for circuit modification, he would incorporate all changes into the PCB design; insuring on-board practicality was still obtainable. Kyle worked closely with Texas Instruments Design experts in order to ensure the board was of a professional standard, which played a critical role in the end of the semester cram for completing product deliverables.

A.1.3 Min-Jae Lee



Min Jae was involved in solving variety of design challenges faced throughout the semester, heavily focused on signal circuitry design of sensor board. At beginning stage of the project, he defined roles of each pins of micro MAVRK and mapped out how each pin corresponds to debugger module and sensor board interface. From there, Kevin was able to decide how to program the CC430, defining input and output pins. During the programming procedure, he supplied Kevin with mathematical solutions on how to convert digitizes value of temperature sensor to actual temperature value. He also helped Kevin on initial setup of coding environment, solving compatibility issues between MAVRK motherboard and computer.

Min Jae played critical role on sensor component selection and design. He was final decision maker on component selection and design. He studied different characteristics of Operation Amplifiers and find out how to implement theoretical Op Amp design to real world application. He also designed a circuitry for reading voltage output from resistive temperature detector. He kept close contact with Jordan and Kyle and in charge of making design iterations requested by sponsor and team member.

In testing and simulation, he had studied new simulation program TINA and simulated circuitry that was not able to test on proto-board level. He also provided solutions to problems on testing components with small package, by implementing adapters that provides conversion between small packing to larger package where testing can be conducted on proto board level.

After sensor board population, he has given large contribution on testing board for errors. He tested functionality of components on populated board and did final modification on errors created by design and component misplacement.

A.1.4 Jordan Bennett



Jordan worked on a variety of design issues throughout the semester, with a focus on establishing an accurate baseline reference and circuitry design. This particular project involved submerging the designed module in to concrete. For the design process, he developed an effective concrete substitute that presented correlating properties to concrete in order to allow for the removal of the module for further iterations. Research was done to find the time required for concrete to settle in various environments, and from there power consumption was derived to ensure enough energy supplied the module for the needed time duration. Jordan established testing parameters that were needed to ensure that the project could function correctly and produce proper measurements in harsh environments, such as high and low temperature and humidity extremes. Calibration experiments were developed by Jordan to maintain accuracy for each sensor. Data acquisition of sensor outputs was documented for validation of accuracy.

Jordan was heavily involved in component selection to meet customer stipulations along with compatibility issues between parts used. He looked in to which constraints were essential for each sub circuit given the requirements from the μ MAVRK processor and the need for accurate and low noise outputs. Jordan designed an alternative design for the sensor board, which proved to be successful when tested. A collaborative group decision was to go with Min-Jae's prototype, based on his incorporation of TI components and that the schematic was already under production in Cadence. Following the design, Jordan began working closely with Min-Jae and his circuit to make calculated changes from TI along with any problems that occurred.

Appendix 2- References

A2.1 Data Sheet Links

"Flat Chip Temperature Sensor Data Sheet." Vishay Beyschlag.
<http://www.vishay.com/docs/28762/28762.pdf>

"CHS-UGS Humidity Sensor Data Sheet." TDK.
http://www.tdk.co.jp/tefe02/eb111_chs.pdf

"TPS6300DRC Data Sheet." Texas Instruments.
<http://www.ti.com/lit/ds/symlink/tps63000.pdf>

"TPS60140PWP Data Sheet." Texas Instruments.
<http://www.ti.com/lit/ds/symlink/tps60140.pdf>

"INA332 Data Sheet." Texas Instruments.
<http://www.ti.com/lit/ds/symlink/ina332.pdf>

"OPA363AIDBV Data Sheet." Texas Instruments.
<http://www.ti.com/lit/ds/symlink/opa363.pdf>

A2.2 Websites

MAVRK Introduction. Lauer M., Kozitsky A., Claassen M., Metelko M., Tracy C. Texas Instruments. 12-2-11 <http://processors.wiki.ti.com/index.php/MAVRK_Introduction>

Hardware Design Guide for the uMAVRK Analog Interface. Claassen M., Howe M. Texas Instruments. 06-27-2011
http://processors.wiki.ti.com/index.php/Hardware_Design_Guide_for_the_uMAVRK_Analog_Interface>

"Chapter 3, Concrete Manual: Mix Design." *Mn-DOT*. 5-694th ed. Minneapolis: n.p., 2003. 300-43. *Minnesota Department of Transportation*. Web. 5 Nov. 2011.
<www.dot.state.mn.us/materials/manuals/concrete/>.

"ASTM Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions." *ASTM E104-85*. E104-85 ed. N.p.: n.p., 1996. Web. 5 Oct. 2011.
<<http://www.astm.org/DATABASE.CART/HISTORICAL/E104-85R96.htm>>.

Name of website. Editor(s) of website. Date of electronic publication. Associated institution. Date of access <URL>.

DipTrace - Professional Schematic & PCB Design Software. Blaze. 2011
<www.diptrace.com>.

Appendix 3: Technical Attachments

		Task Name	Duration	Start	Finish	Pi	Resource Names
1		Research On project	16 days	Mon 9/19/11	Fri 10/7/11		
2		Tempreture sensor	16 days	Mon 9/19/11	Fri 10/7/11		Min-Jae
3		humidity sensor	16 days	Mon 9/19/11	Fri 10/7/11		Jordan
4		uMAVRK interface	16 days	Mon 9/19/11	Fri 10/7/11		Kevin
5		Testing environment	16 days	Mon 9/19/11	Fri 10/7/11		Kyle
6		Design Tested on protoboard level	14 days	Wed 9/28/11	Thu 10/13/11	1	Jordan,Kyle,Min-Je
7		Obtain Parts needed for building design	0 days	Tue 9/27/11	Tue 9/27/11		Kyle
8		Test Humidity sensor functionality	2 days	Mon 10/10/11	Tue 10/11/11		Jordan
9		Test Tempreture sensor functionality	3 days	Wed 9/28/11	Fri 9/30/11		Min-Jae
10		Op-Amp Signal Conditioning(if necessary)	2 days	Wed 10/12/11	Thu 10/13/11	8,9	Min-Jae
11		Test Environment design	5 days	Mon 10/10/11	Fri 10/14/11	1	Jordan
12		Order Materials needed for Testing Environment	3 days	Mon 10/10/11	Wed 10/12/11		Jordan
13		Build testing environment	2 days	Thu 10/13/11	Fri 10/14/11	12	Jordan
14		MSP430 Programming	5 days	Mon 10/10/11	Fri 10/14/11	1	Kevin
15		uMAVRK pins Mapped out	1 day	Mon 10/10/11	Mon 10/10/11		Min-Jae
16		CC430 Programed	5 days	Mon 10/10/11	Fri 10/14/11		Kevin
17		MSP430 Programmed	5 days	Mon 10/10/11	Fri 10/14/11		Kevin
18		sensor borad testing using uMAVRK	7 days	Mon 10/17/11	Mon 10/24/11	6,14	Kevin,Min-Jae
19		Test ADC conversion	2 days	Mon 10/17/11	Tue 10/18/11		Kevin
20		Test RF signal(Rx Tx)	2 days	Wed 10/19/11	Thu 10/20/11	19	Kevin
21		Circuit Modification for DSP difference	3 days	Fri 10/21/11	Mon 10/24/11	20	Min-Jae
22		PCB Board Fabrication(using Allegro)	7 days	Tue 10/25/11	Wed 11/2/11	18	
23		Circuit Simulation using TINA	1 day	Tue 10/25/11	Tue 10/25/11		Kyle
24		Grabber file created	1 day	Tue 10/25/11	Tue 10/25/11		Jordan,Kevin
25		sending& receiving PCB	6 days	Wed 10/26/11	Wed 11/2/11	23,2	Kyle
26		Enclosure Design	4 days	Thu 11/3/11	Tue 11/8/11	22	Jordan
27		Modify Enclosure to expose sensors	3 days	Thu 11/3/11	Mon 11/7/11		Jordan
28		Assmble Proto module	1 day	Tue 11/8/11	Tue 11/8/11	27	Jordan
29		Test 1st prototype sensor module	6 days	Wed 11/9/11	Wed 11/16/11	26	Jordan,Kevin,Kyle,
30		Gather Test Data	4 days	Wed 11/9/11	Mon 11/14/11		Jordan
31		MAVRK modification	1 day	Tue 11/15/11	Tue 11/15/11	30	Kevin
32		Circuit Modification	1 day	Tue 11/15/11	Tue 11/15/11	30	Kyle,Min-Jae
33		Fabricate Final Protoboard	10 days	Thu 11/17/11	Tue 11/29/11	29	
34		design Allegro PCB layout containing uMAVRK, Sensor module, power module	3 days	Thu 11/17/11	Sat 11/19/11		Jordan,Kevin
35		Send&Receive PCB	7 days	Mon 11/21/11	Tue 11/29/11	34	Kyle
36		Assemble final module	4 days	Thu 12/1/11	Mon 12/5/11	33	Jordan,Kevin,Kyle,
37		Final Demonstration of module with test enviroment	3 days	Thu 12/1/11	Sun 12/4/11		Jordan,Kevin,Kyle,Mi
38		Non-technical tasks	62 days?	Tue 9/27/11	Mon 12/12/11		
39		update preproposal	11 days	Sun 10/2/11	Thu 10/13/11		
40		practice oral presentation	5 days	Fri 10/7/11	Wed 10/12/11		
41		Progress Report 1	23 days	Tue 9/27/11	Sat 10/22/11		
42		Oral Proposal Presentations	3 days	Wed 10/19/11	Fri 10/21/11		
43		First project demonstration for facilitator	2 days?	Tue 11/1/11	Wed 11/2/11		
44		Individual Application Notes due to facilitators	3 days?	Mon 11/7/11	Wed 11/9/11		
45		Team Technical Lectures	4 days?	Tue 11/8/11	Fri 11/11/11		
46		Progress Report # 2 and Demo #2 due to facilit	4 days?	Fri 11/11/11	Wed 11/16/11		
47		Design Issues paper due	2 days?	Sat 11/19/11	Mon 11/21/11		
48		Professional self-assessment papers due	51 days?	Tue 9/27/11	Tue 11/29/11		
49		Final Proposal	5 days?	Mon 10/17/11	Fri 10/21/11		
50		Design Day Program Page	4 days	Tue 10/4/11	Fri 10/7/11		
51		Design Day Preparation + posters + Final Notebooks + CD	7 days?	Thu 12/1/11	Thu 12/8/11		
52		Technical Lecture Topic Form	3 days?	Sun 10/16/11	Tue 10/18/11		
53		Photocopy Of Engineering Notebooks	3 days?	Mon 10/24/11	Wed 10/26/11		
54		Final Reports, updates on website	3 days?	Sun 12/4/11	Tue 12/6/11		
55		Evaluation of individual Team members	2 days?	Sun 12/11/11	Mon 12/12/11		

Figure 22: Gantt Chart

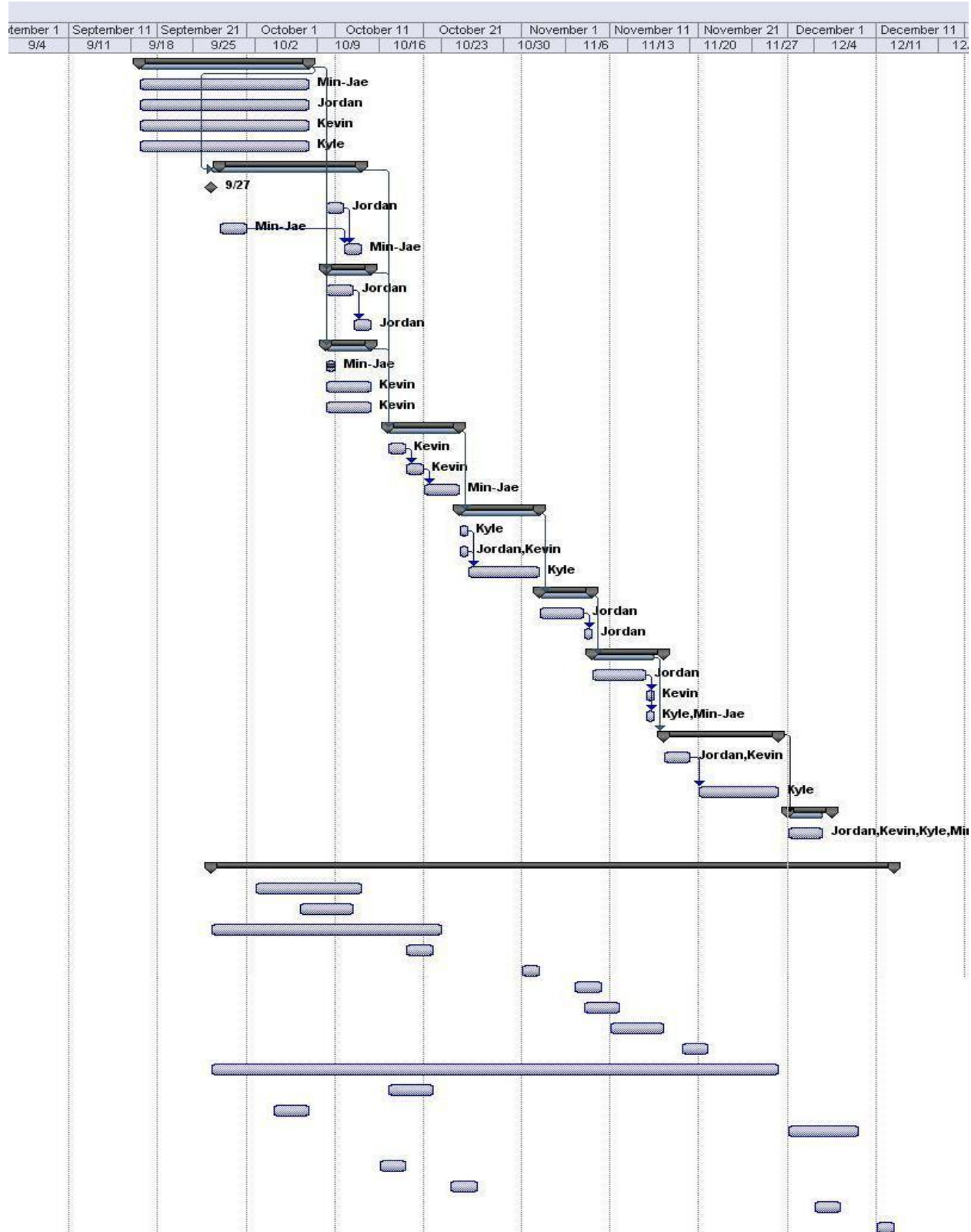


Figure 23: Gantt chart timeline

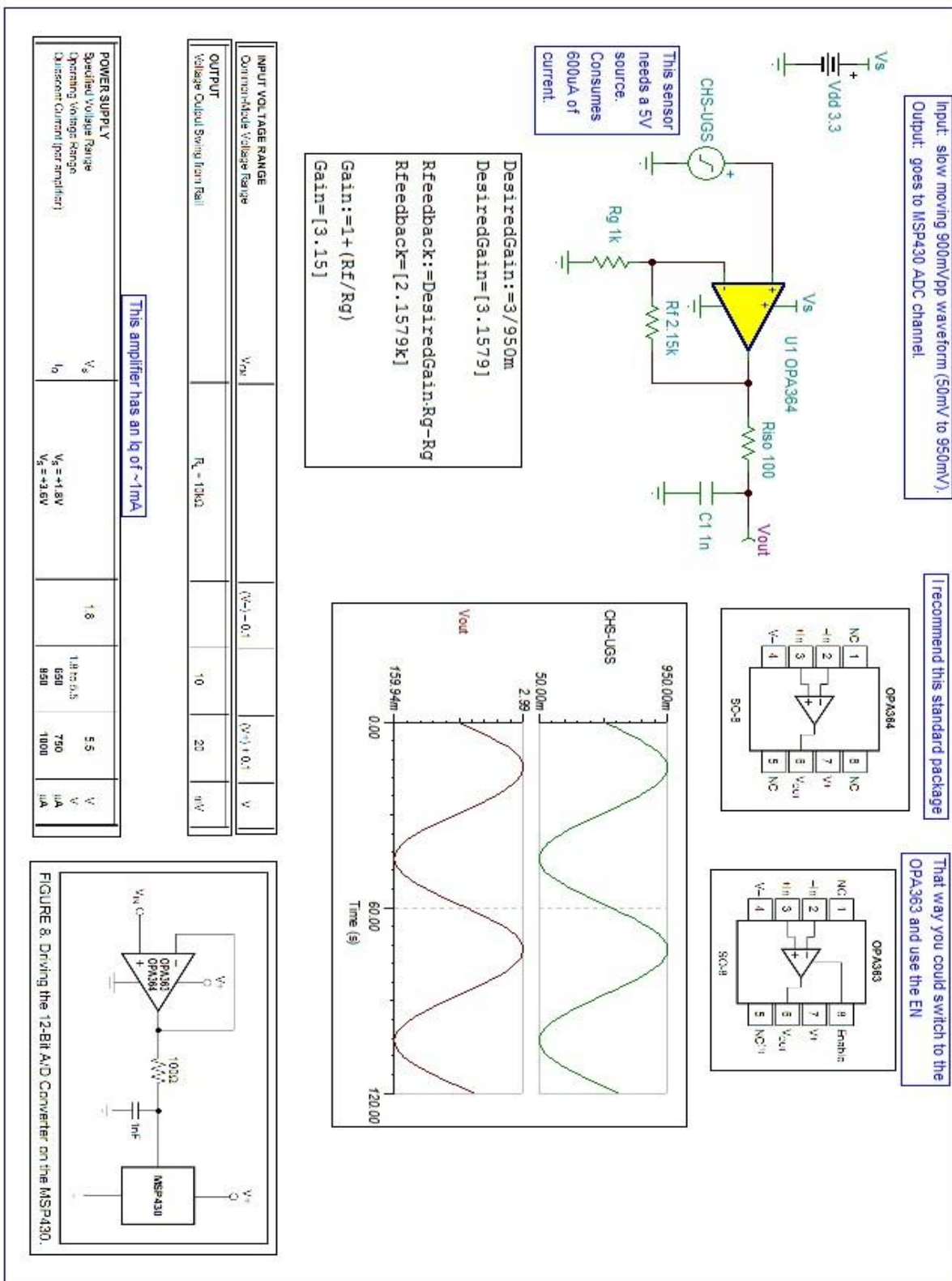


Figure 24: OPA364 TINA Simulation

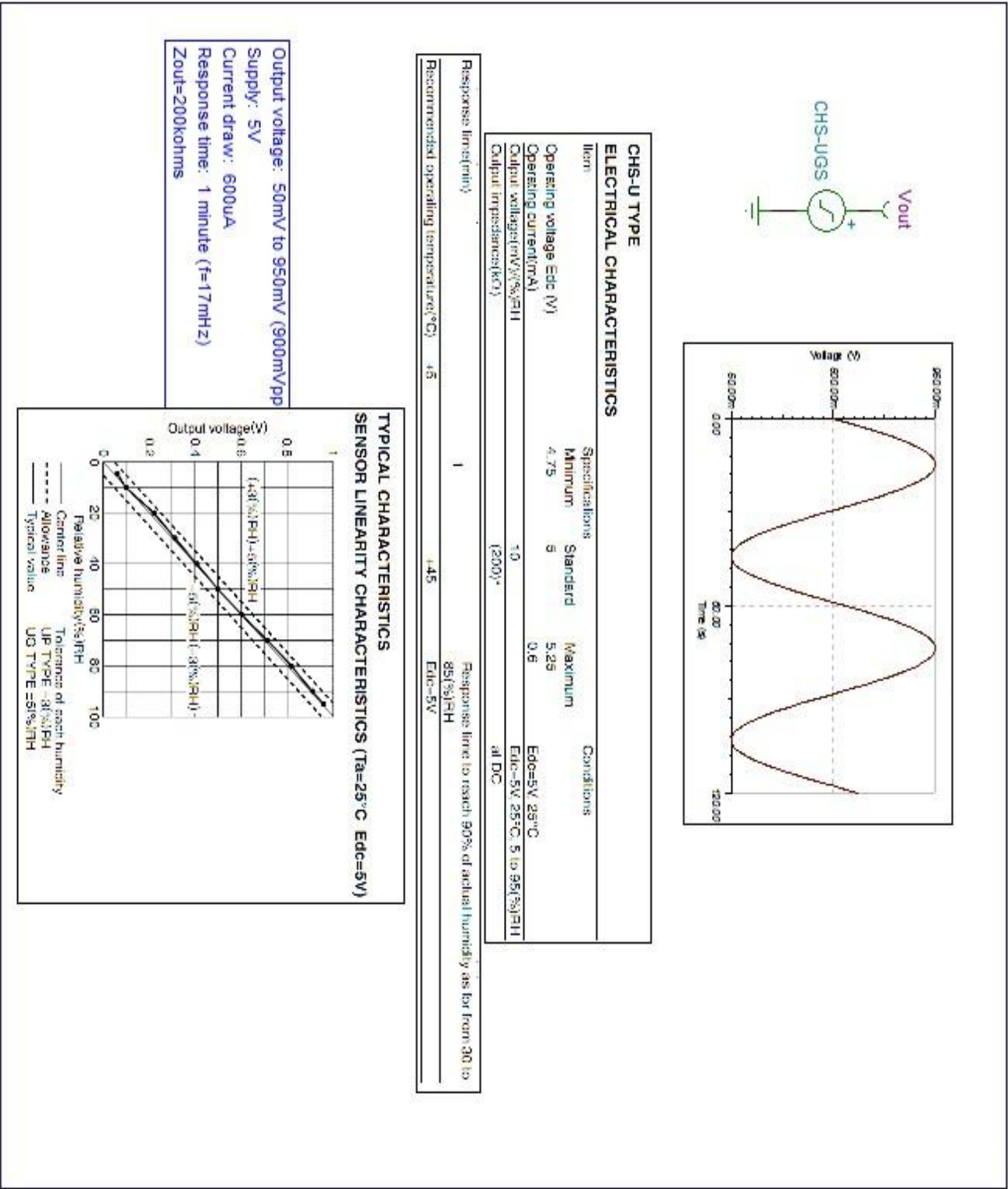


Figure 25:Humidity Sensor TINA Model

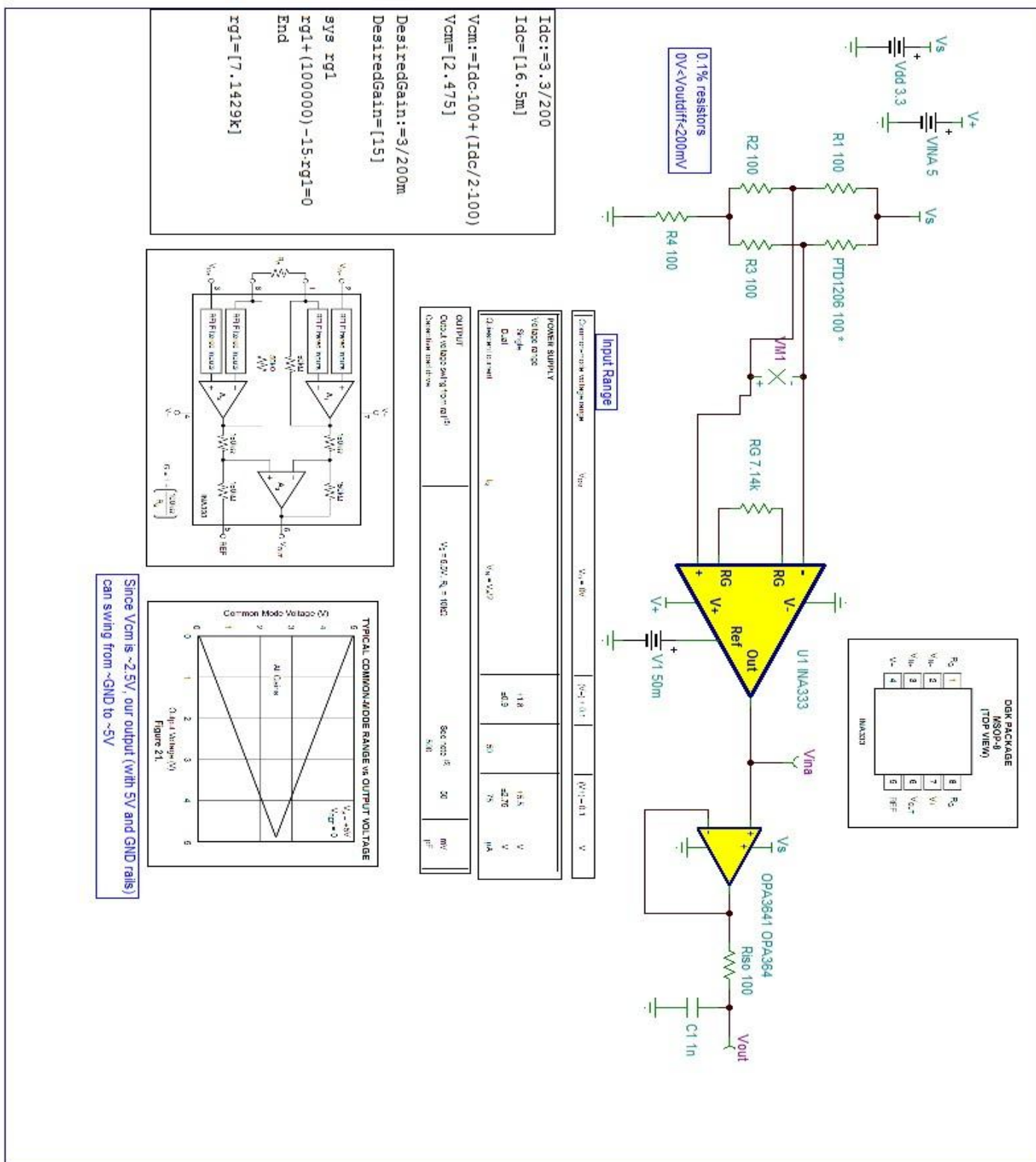


Figure 26: Temperature Sensor Circuit TINA Simulation

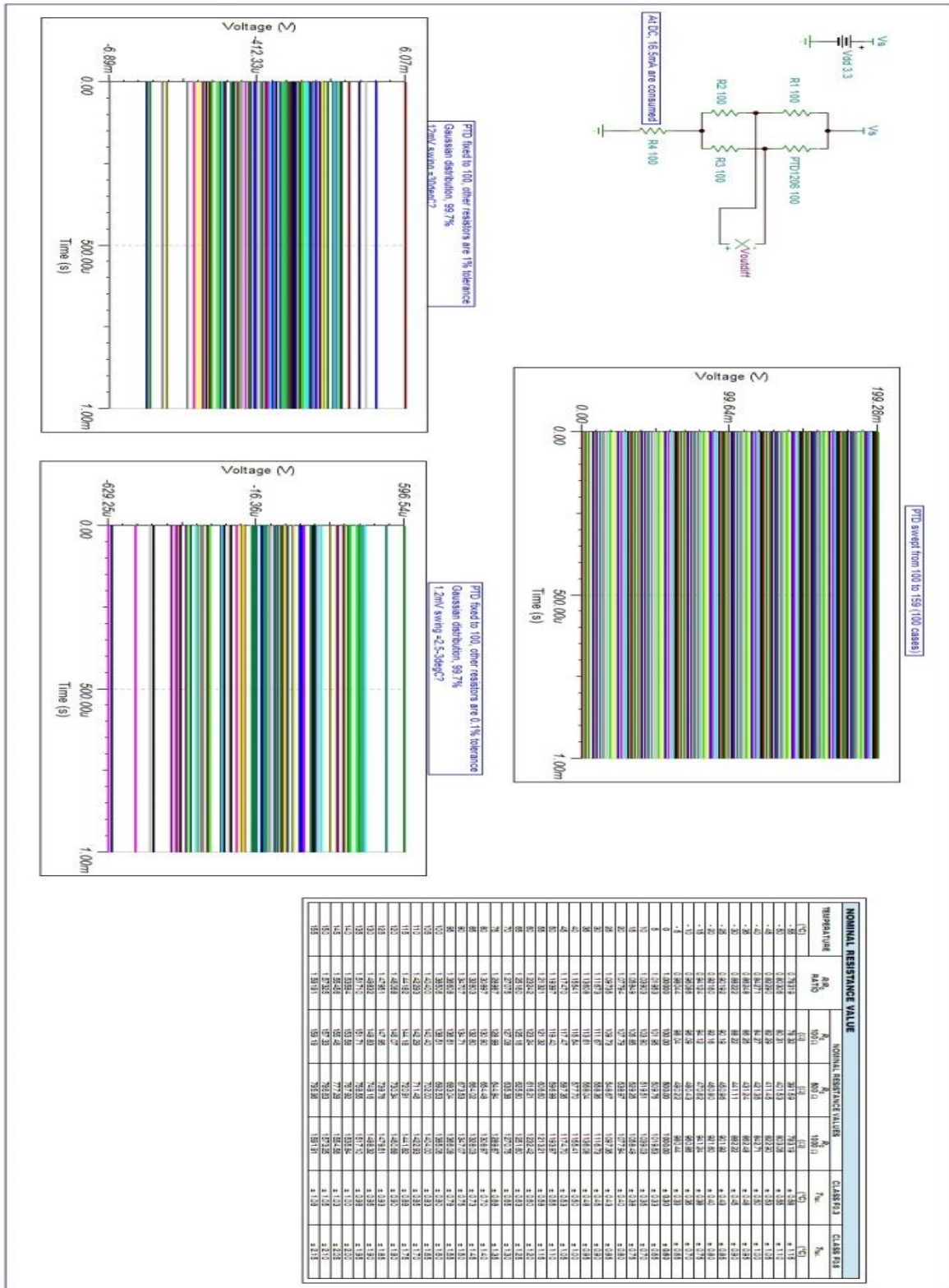


Figure 27: Temperature Sensor TINA Simulation

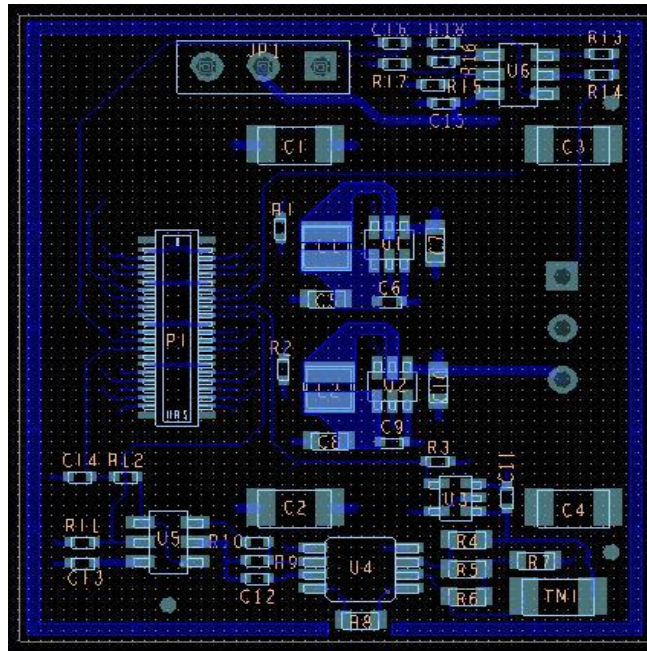


Figure 28: PCB Top Assembly (Layer 1)

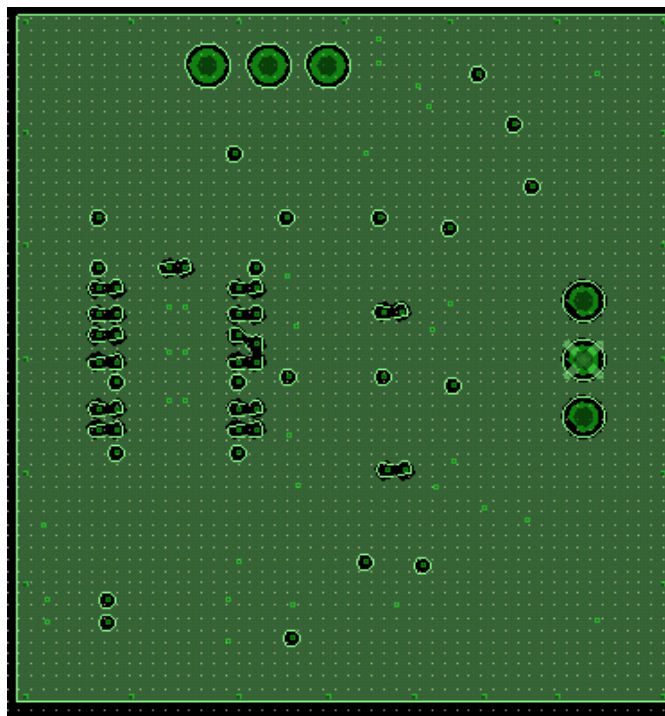


Figure 29: PCB Ground Assembly (Layer 2)

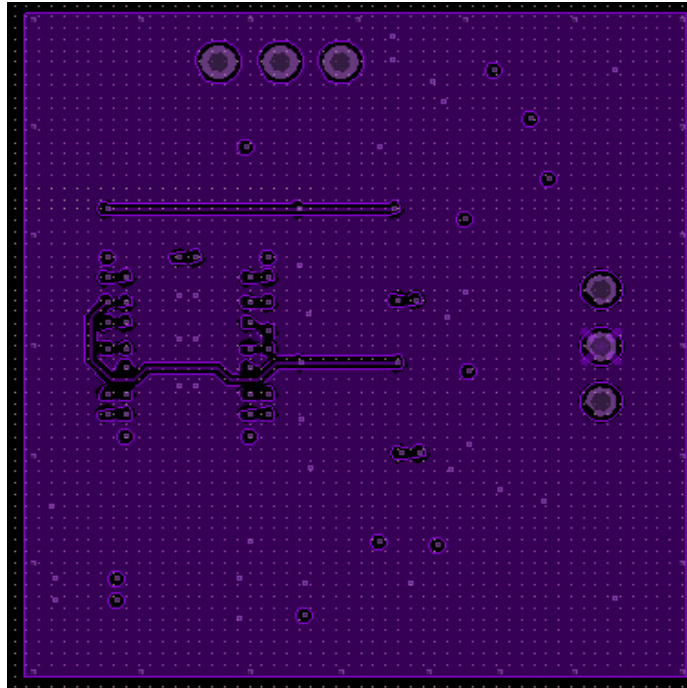


Figure 30: Signal Plane (Layer 3)

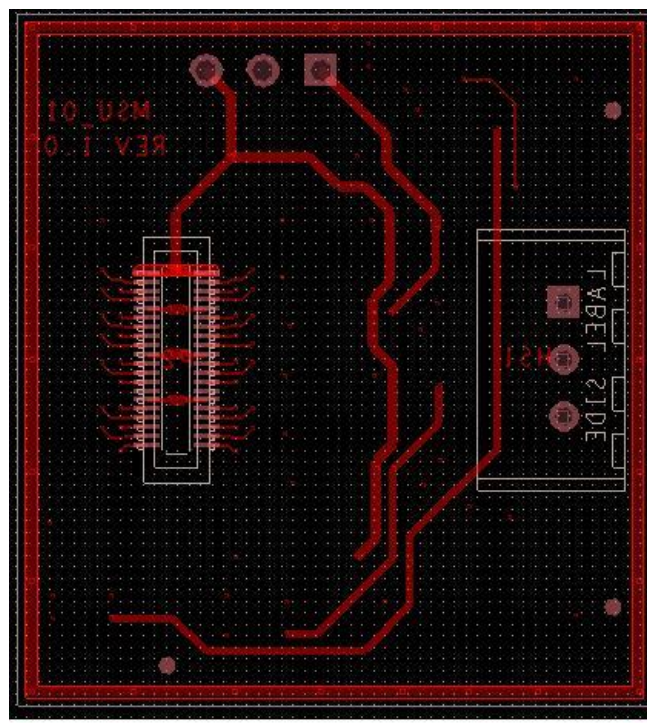


Figure 31: PCB Bottom Assembly (Layer 4)



Figure 32: PCB Fabrication Notes

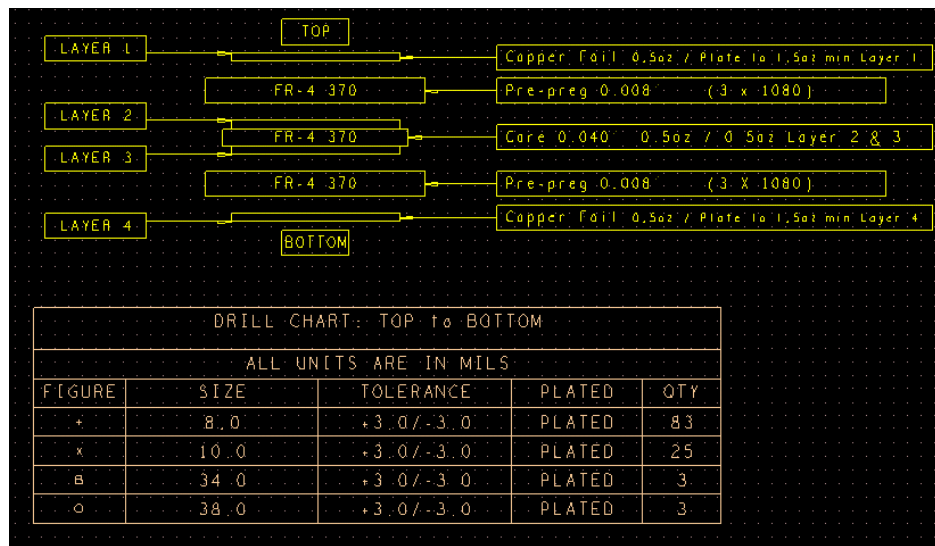
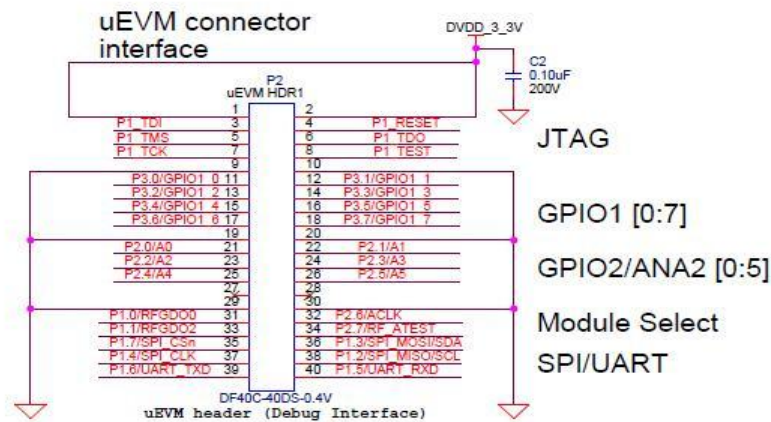
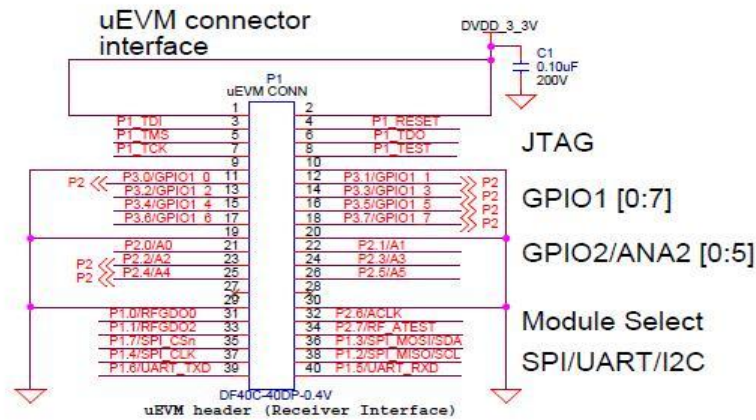


Figure 33: PCB Fabrication notes

A3.5 Schematic



Note: Used as spacers.

C3 0.10uF 200V

C4 0.10uF 200V

Figure 35: Schematic of Front and Rear Board Connectors

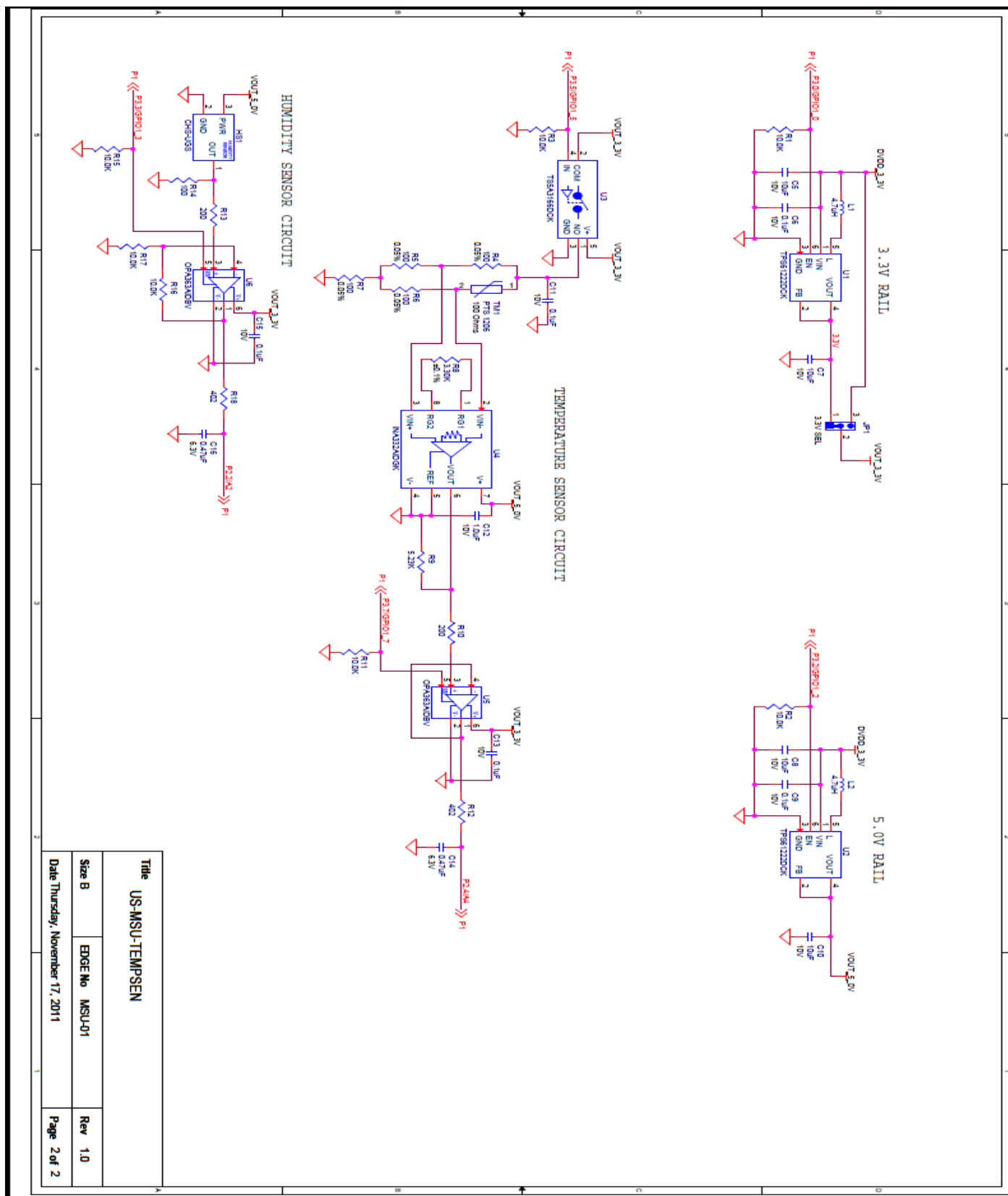


Figure 36: Sensor Module Circuit

$$B = (400 * (15625 * V_{out}^2 - 2263500 * V_{out} + 198359056)^{1/2} - 200000 * V_{out} + 1156900) / (1500 * V_{out} - 44767)$$

$$\text{Temp} = 461410623124985856 / 136358332192861 - (2048 * 5^{1/2} * (7304443836598584599289973921525 - 9595364594572361067296456704 * b)^{1/2}) / 3408958304821525$$

Figure 37: Matlab Code for Software Iteration #3