University of Puerto Rico
Mayagüez Campus
Mayagüez, Puerto Rico
Department of Electrical and Computer Engineering

WindTel: Wind Tunnel Automation Using Embedded System Technologies
Report #3

by

Luis O. Vega Maisonet
Nelson G. Rodriguez Ortiz (Leader)
Kahlil J. Fonseca Garcia
Misael Valentín Feliciano

For: Dr. Manuel Jiménez
Course: ICOM-4217, Section 080
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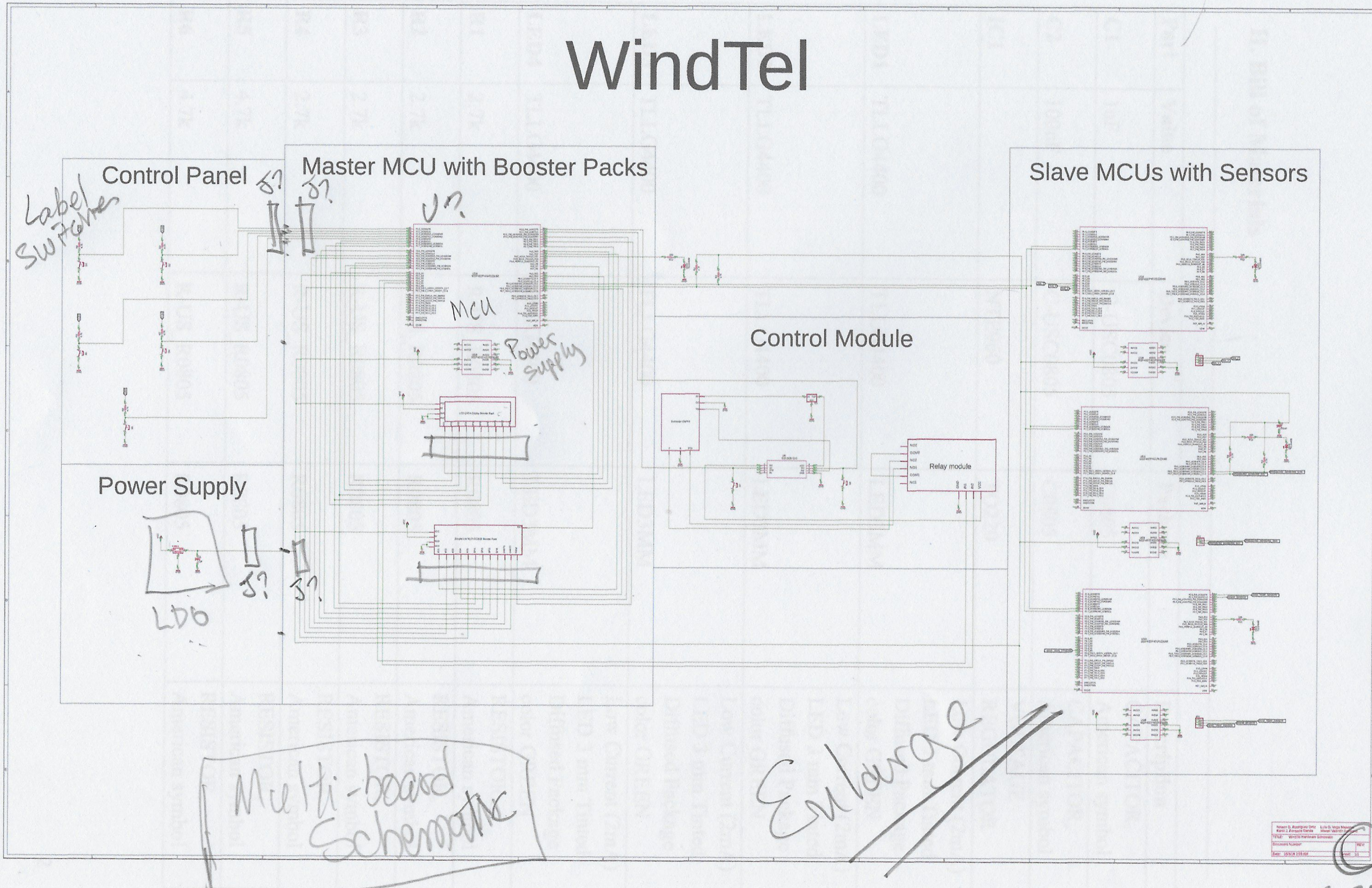

WindTel
Control Panel
Master MCU with Booster Packs
Slave MCUs with Sensors
Control Module
Relay module
Power Supply
Label switches
J?
J?
U?
MCU
Power supply
LDO
J?
J?
Multi-board Schematic
Enlarge

SIZE
A, B, C, D

II. Bill of Materials

Part	Value	Device	Package	Description
C1	1uF	C-USC0805	C0805	CAPACITOR, American symbol
C2	100nF	C-USC0805	C0805	CAPACITOR, American symbol
IC1		NTE960	TO220	VOLTAGE REGULATOR
LED1	TLLG4400	TLLG4400	LED3MM	Low Current (2mA) LED 3 mm Tinted Diffused Package color GREEN
LED2	TLLG4400	TLLG4400	LED3MM	Low Current (2mA) LED 3 mm Tinted Diffused Package color GREEN
LED3	TLLG4400	TLLG4400	LED3MM	Low Current (2mA) LED 3 mm Tinted Diffused Package color GREEN
LED4	TLLG4400	TLLG4400	LED3MM	Low Current (2mA) LED 3 mm Tinted Diffused Package color GREEN
R1	2.7k	R-US_R0805	R0805	RESISTOR, American symbol
R2	2.7k	R-US_R0805	R0805	RESISTOR, American symbol
R3	2.7k	R-US_R0805	R0805	RESISTOR, American symbol
R4	2.7k	R-US_R0805	R0805	RESISTOR, American symbol
R5	4.7k	R-US_R0805	R0805	RESISTOR, American symbol
R6	4.7k	R-US_R0805	R0805	RESISTOR, American symbol

R7	4.7k	R-US_R0805	R0805	RESISTOR, American symbol
R8	4.7k	R-US_R0805	R0805	RESISTOR, American symbol
R9	4.7k	R-US_R0805	R0805	RESISTOR, American symbol
R10	330	R-US_M0805	M0805	RESISTOR, American symbol
R11	330	R-US_M0805	M0805	RESISTOR, American symbol
R12	330	R-US_M0805	M0805	RESISTOR, American symbol
R13	330	R-US_M0805	M0805	RESISTOR, American symbol
S1		31-XX	B3F-31XX	OMRON SWITCH
S2		31-XX	B3F-31XX	OMRON SWITCH
S3		31-XX	B3F-31XX	OMRON SWITCH
S4		31-XX	B3F-31XX	OMRON SWITCH
S5		31-XX	B3F-31XX	OMRON SWITCH
S6		31-XX	B3F-31XX	OMRON SWITCH
S7		31-XX	B3F-31XX	OMRON SWITCH
U1	MSP432P401R LAUNCHPAD	MSP432P401R LAUNCHPAD	ZXH0080A	
U2	MSP432P401R LAUNCHPAD	MSP432P401R LAUNCHPAD	ZXH0080A	
U3	MSP432P401R LAUNCHPAD	MSP432P401R LAUNCHPAD	ZXH0080A	
U4	MSP432P401R LAUNCHPAD	MSP432P401R LAUNCHPAD	ZXH0080A	
U5	MSP432P401R LAUNCHPAD	MSP432P401R LAUNCHPAD	ZXH0080A	
U6	DS1809-010	DS1809-010	21-0043D_8	DS1809 Series 64 Tabs 20 kOhm Non-Volatile Through Hole Digital POT - PDIP-8
V-REG-1		MCP1702	TO92	Voltage Regulator

LCD		QVGA Display BoosterPack	BOOSTXL-K350QVG-S1	The BOOSTXL-K350QVG-S1 Kentec QVGA Display BoosterPack™ is an easy-to-use plug-in module for adding a touch-screen color display to your LaunchPad™ design.
Wi-Fi Module		SimpleLink™ Wi-Fi® CC3100 wireless network processor BoosterPack	CC3100BOOST	
Relay		Relay Module	SRD-05VDC-SL-C	

III. Power and Timing Analysis

Missing Mounting HW
- Connect.
- Enclosure
- Headers
- Spacers
- Wire
- Boards

A. Power Analysis

This automated system will be energized by a custom-made power supply. An Enercell AC to DC Travel Charger will be connected throw a 120VAC source. The Enercell charger will provide a 5V DC voltage to a NTE960 IC (a low-dropout regulator) that will provide 3.3V DC voltage. This power supply will provide the two voltages currently mentioned in parallel and it will be located inside the wind tunnel laboratory. The reason these regulated voltages were chosen is because the MCU pins cannot support Puerto Rico's standard wall outlet voltage of 120VAC and these are the voltages required to operate the peripheral components that will be connected to the MCU.

A MSP432P401R MCU will serve as a master in a I^2C communication protocol with a set of three slave MSP432P401R MCU's. Each of the MCU's will be connected to peripheral devices. The system operating conditions are the following:

define terms

I_{IH} I_{OH}

Name	VDD_{Rec}	VIH	VIL	V_{OH}	V_{OL}	I_{in}	I_{out}	I_{leak}
MSP432P401R (x4)	5V	2.25V	0.75V	2.7V	0.60V	<2mA	1mA	40nA

Missing I_{DD} or I_{CC}

no load?

Relays or Solenoid spec

Wind Speed Window Actuator (SM-42BYG011)	12V	NA	NA	NA	NA	NA	NA	NA
Barometric Pressure Sensor (BMP085) (x48)	3.3V	2.64V	0.66V	1.32V	0.3V	7.7mA	1.5mA	NA
Humidity and Temperature Sensor (DHT11)	5V	NA	NA	NA	NA	2.5mA	1mA	150uA
Instrumentation Amplifiers (x3) (INA125)	12V	2.7V	0.1V	NA	NA	15uA	NA	NA
BOOSTXL-K350QVG-S1 QVGA Display BoosterPack	5V	2.2V	0.6V	2.4V	0.4V	0.6mA	1.2mA	1uA
Wind Vane Sensor (Resistor)	3.3V	NA	NA	NA	NA	10mA	NA	NA
Anemometer Sensor (US-1881)	5V	NA	NA	0.4V	0.4V	2mA	NA	0.01uA
Relay (SRD-05VDC-SL-C)	5V	NA	NA	NA	NA	85mA	NA	NA
Potentiometer (DS1809-010)	5V	2V	0.8V	NA	NA	0.5mA	1mA	1uA
LDO (MCP1702)	5V	NA	NA	NA	N3A3kHz	NA	250mA	N5uA

Double check working condition

Based on the datasheet of the MCU each port pin can operate adequately if it as an output current less than 20mA and an input current less than 2mA. A worst-case scenario was taking into consideration for calculating each of the port currents. Pins 1.5, 1.6, 1.7, 2.3, 2.5, 2.7, 3.0, 3.2, 3.3, 3.5, 3.6, 3.7, 4.0, 4.1, 4.6, 5.0, 5.1, 5.6, 6.1, and 6.6, are connected directly to the LCD and Wi-fi modules hence the currents are negligible since each module is an extension of the MCU. Pins 2.4, 2.6, 3.1, 3.4, 4.3, 4.4, 4.5,4.7, 5.2, 5.5 and 5.7 are not used.

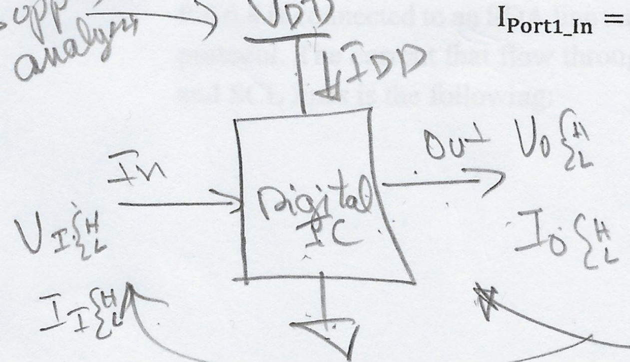
Need to consider the Max package Dissipation

Port 1

Five pushbuttons are connected from pins 1.0 to 1.4. To make the current less than 2mA a resistance of 4.7kΩ was selected.

Power supply analysis

$$I_{Port1\_In} = \left(\frac{V_{Source} - V_{MCU\_OL}}{R}\right)(5\text{ pushbuttons})$$



Loading & compatibility analysis

$$I_{Port1\_In} = \left(\frac{3.3V-0.60V}{4.7k\Omega}\right)(5\ \text{pushbuttons})$$

$$I_{Port1\_In} = 0.574mA(5\ \text{pushbuttons})$$

$$I_{Port1\_In} = 2.87mA$$

Momentary. Not all at a time

Port 2

Pins 2.0 and 2.1 are connected to a DS1809-010 (Potentiometer Resistance). These two pins are setup into high drive operation where each pin can withstand up to 20mA.

$$I_{Port2\_Out} = \left(\frac{V_{MCU_{OH}} - V_{Potentiometer_{IL}}}{R_{Potentiometer}}\right)$$

$$I_{Port2\_Out} = \frac{2.7V - 0.8V}{0.1k\Omega}$$

$$I_{Port2\_Out} = 19mA$$

!!! Consider a IC buffer

Port 4

Pin 4.2 is connected to a LED. To make the current less than 2mA a resistance of 1kΩ was selected.

$$I_{Port4\_Out} = \frac{V_{MCU\_OH} - V_F}{R_F}$$

$$I_{Port4\_Out} = \frac{2.7V - 1.64V}{1k\Omega}$$

$$I_{Port4\_Out} = 1.06mA$$

mili Candle Check Brightness

Consider High brightness LED (low current)

Port 5

Pins 5.3 and 5.4 are sets as inputs and are connected directly to the relay module. The current that the relay module sends to the MCU is 1mA.

$$I_{Port5\_In} = 1mA(2\ \text{relay module lines})$$

$$I_{Port5\_In} = 2mA$$

Port 6

Pin 6.4 is connected to an SDA line and pin 6.5 are connected to a SCL line of a I²C communication protocol. The current that flow through the 3.3V source to the R_D resistance and then to an SDA and SCL lines is the following:

$$I_{Port1\_In} = \left(\frac{3.3V - 0.60V}{4.7k\Omega}\right)(5\ pushbuttons)$$

$$I_{Port1\_In} = 0.574mA(5\ pushbuttons)$$

Momentary: Not all at a time

$$I_{Port1\_In} = 2.87mA$$

Port 2

Pins 2.0 and 2.1 are connected to a DS1809-010 (Potentiometer Resistance). These two pins are setup into high drive operation where each pin can withstand up to 20mA.

$$I_{Port2\_Out} = \left(\frac{V_{MCU_{OH}} - V_{Potentiometer_{IL}}}{R_{Potentiometer}}\right)$$

$$I_{Port2\_Out} = \frac{2.7V - 0.8V}{0.1k\Omega}$$

!!! consider a DC buffer

$$I_{Port2\_Out} = 19mA$$

Port 4

Pin 4.2 is connected to a LED. To make the current less than 2mA a resistance of 1kΩ was selected.

$$I_{Port4\_Out} = \frac{V_{MCU\_OH} - V_F}{R_F}$$

mili Candle

Check Brightness

$$I_{Port4\_Out} = \frac{2.7V - 1.64V}{1k\Omega}$$

$$I_{Port4\_Out} = 1.06mA$$

Consider High brightness LED (low current)

Port 5

Pins 5.3 and 5.4 are sets as inputs and are connected directly to the relay module. The current that the relay module sends to the MCU is 1mA.

$$I_{Port5\_In} = 1mA(2\ relay\ module\ lines)$$

$$I_{Port5\_In} = 2mA$$

Port 6

Pin 6.4 is connected to an SDA line and pin 6.5 are connected to a SCL line of a I²C communication protocol. The current that flow through the 3.3V source to the R_D resistance and then to an SDA and SCL lines is the following:

$$I_{Port6_{I2C}} = \left(\frac{V_{Source} - V_{MCU\_OL}}{R_D}\right)(2\ lines)$$

$$I_{Port6_{I2C}} = \left(\frac{3.3V - 0.60V}{2.7k\Omega}\right)(2\ lines)$$

$$I_{Port6_{I2C}} = 1mA(2\ lines)$$

$$I_{Port6_{I2C}} = 2mA$$

The total current that the MCU produces in a worst-case scenario is the following:

$$I_{Port} = I_{Port1} + I_{Port2} + I_{Port3} + I_{Port4} + I_{Port5} + I_{Port6}$$

$$I_{Port} = 2.87mA + 19mA + 0mA + 1.06mA + 2mA + 2mA$$

$$\boxed{I_{Port} = 26.93mA}$$

Package Power and Temperature

The package power parameters of the MSP432P401R are found in the Texas Instruments PowerPad Thermally Enhanced Package Application Report. The junction to case thermal resistance (θ_{JC}) is equal to 5°C and the case to ambient thermal resistance θ_{JA} is equal to 55°C. The package power is calculated as follows:

$$P_{PKG} = V_{DD} I_{PKG}$$

$$P_{PKG} = V_{DD}(I_{DD} + I_{Port})$$

$$P_{PKG} = (3.3V)(2mA + 26.93mA)$$

$$P_{PKG} = 95.467mW$$

The package temperature is calculated as follows:

$$T_{PKG} = P(\theta_{JC} + \theta_{JA}) + T_A$$

$$T_{PKG} = (95.467mW)(5°C + 55°C) + 25°C$$

$$T_{PKG} = 30.728°C$$

OK or not?

B. Timing Analysis

Minimum Pulse Width

The minimum pulse width checks are done to ensure that width of the clock signal is wide enough to have a functional system. This determines the constraints for the processor in terms of clock speed and frequency division. For the WindTel system, the components that require interfacing at various frequencies are:

- BMP085 - Barometric Pressure Sensor
- US1881 - Hall-effect Sensor for Fan Anemometer
- Kentec QVGA Display BoosterPack - Touchscreen color display
- DHT11 - Humidity and Temperature Sensor
- Simple Link Wi-Fi CC3100 Booster Pack - Wi-Fi module
- DS1809-010 - Potentiometer
- MCP1702 - LDO
- INA125 - Instrumentation Amplifier

BMP085 - Barometric Pressure Sensor

The Barometric Pressure Sensor uses the I^2C bus, with a maximum frequency of 3.4 MHz, for a minimum pulse width of 0.29 us. I^2C defines different speed grades for maximum rates of 100 kbps in standard mode, 400 kbps in full speed mode, 1 mbps in fast mode, 3.2 mbps in high speed mode, and so on. These are maximum clock rates; the actual rate will be defined by the master MCU through the SCL line.

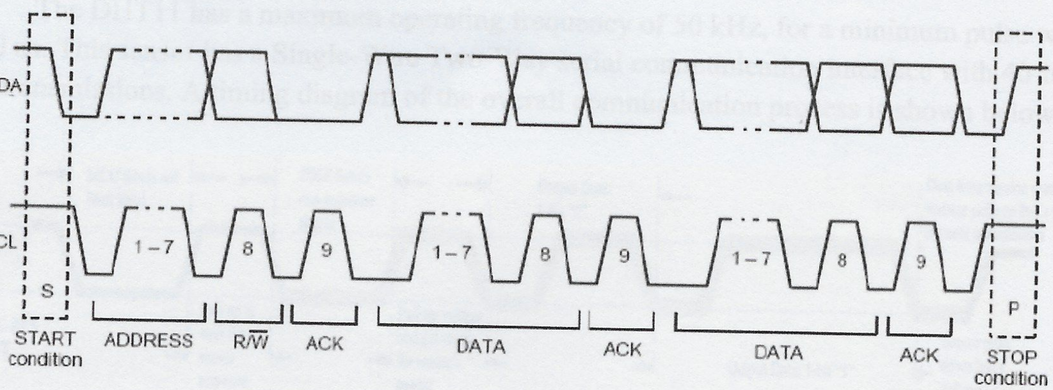


Fig. 1: BMP085 I^2C Protocol timing diagram from [4]

fck?

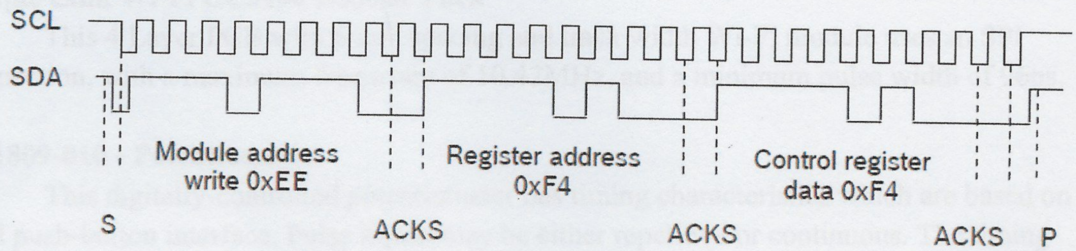


Fig. 2: BMP085 Pressure Measurement Start timing diagram from [4]

US1881 - Hall-effect Sensor for Fan Anemometer

The fan anemometer will use a Hall-effect sensor which sends two pulses for every fan blade rotation. This Hall-effect sensor has a maximum frequency of 10 kHz, for a minimum pulse width of 0.1 ms. The fan anemometer installed at the wind tunnel has a maximum rotation speed of 4500 RPM. Since there are 2 pulses per rotation, we get a maximum pulse speed of 9000 ppm, or 150 pps. This corresponds to 150 Hz or a minimum pulse width of 6.67 ms, which is well above the 0.1 ms minimum pulse width of the US1881 Hall-effect sensor.

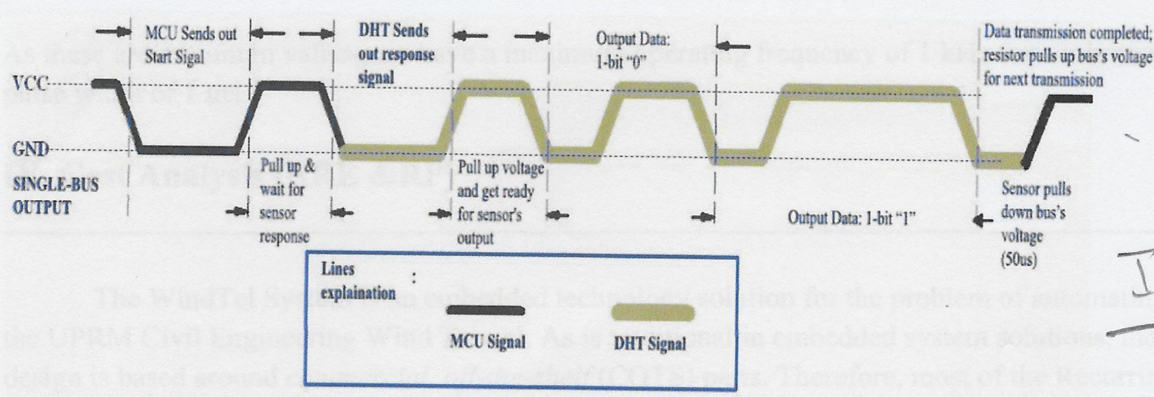
Kentec QVGA Display BoosterPack - Touchscreen color display

The 3.5-inch QVGA display uses an SPI connection, with a maximum frequency of 10.42 MHz, and a minimum pulse width of 96 ns. The frequency will be set to comply with the requirements of the other components.

!!!

DHT11 - Humidity and Temperature Sensor

The DHT11 has a maximum operating frequency of 50 kHz, for a minimum pulse width of 20 us. This sensor has a Single-Wire Two-Way serial communication interface with 40-bit data transmissions. A timing diagram of the overall communication process is shown below.



I^2C

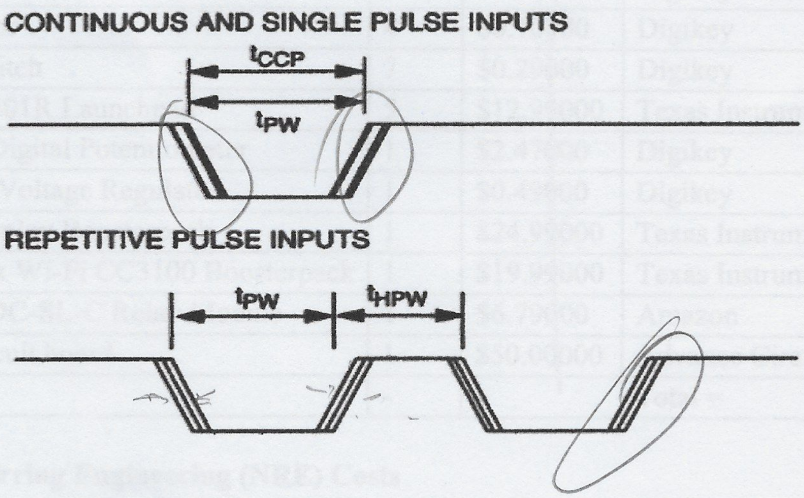
Fig. 3: DHT11 Overall communication process timing diagram from [5]

Simple Link Wi-Fi CC3100 Booster Pack

This 4 Layer PCB with 6 mm spacing and track width Wi-Fi module uses an SPI connection, with a maximum frequency of 10.42MHz, and a minimum pulse width of 96ns.

DS1809-010 - Potentiometer

This digitally-controlled potentiometer has timing characteristics which are based on a dual push-button interface. Pulse inputs may be either repetitive or continuous. The timing characteristics for each are illustrated in the figure below.



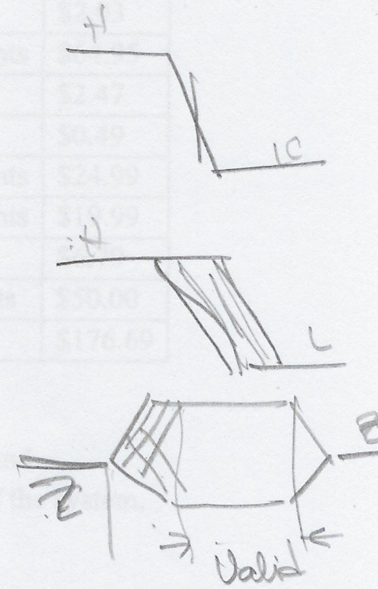


Fig. 4: DS1809-010 pushbutton timing diagram from [9]

Where

t_{CCP} (continuous pulse) = 1 ms

t_{PW} (pulse width) = 1 ms

t_{HPW} (repetitive pulse high time) = 1 ms

As these are minimum values, we have a maximum operating frequency of 1 kHz for a minimum pulse width of 1 ms.

IV. Cost Analysis (NRE &RP)

The WindTel System is an embedded technology solution for the problem of automating the UPRM Civil Engineering Wind Tunnel. As is traditional in embedded system solutions, the design is based around *commercial, off-the-shelf* (COTS) parts. Therefore, most of the Recurring Production (RP) costs will go toward these COTS parts.

A. Recurring Production (RP) Costs

Part	Units	Cost / Unit	Vendor	Cost
1 uF Capacitor	1	$0.10000	Digikey	$0.10
100 nF Capacitor	1	$0.18000	Digikey	$0.18
NTE960 Voltage Regulator	1	$1.40000	Newark	$1.40
Green LED	4	$0.50000	Digikey	$2.00
2.7k Resistor	4	$0.10000	Digikey	$0.40
4.7k Resistor	5	$0.10000	Digikey	$0.50
330 Resistor	4	$0.10000	Digikey	$0.40
Omron Switch	7	$0.29000	Digikey	$2.03
MSP432P401R Launchpad	5	$12.99000	Texas Instruments	$64.95
DS1809 Digital Potentiometer	1	$2.47000	Digikey	$2.47
MCP1702 Voltage Regulator	1	$0.49000	Digikey	$0.49
QVGA Display Boosterpack	1	$24.99000	Texas Instruments	$24.99
SimpleLink Wi-Fi CC3100 Boosterpack	1	$19.99000	Texas Instruments	$19.99
SRD-05VDC-SL-C Relay Module	1	$6.79000	Amazon	$6.79
Printed circuit board	1	$50.00000	Advance Circuits	$50.00
-	-	-	Total =	$176.69

B. Non-Recurring Engineering (NRE) Costs

The recurring engineering costs consists of the costs that go into research and development (R&D), as well as the cost of labor that goes into the development of the system. We approximate these costs with the following formula:

$$NRE = DT * R,$$

where DT is an estimation of the system development time over the course of the semester and R is the average hourly rate of an Embedded Systems Engineer.

We make the following assumptions in our estimation of the development time:

1. System development commenced 1 week after beginning of the semester.
2. System development will be finished on the 21st of November.
3. Each of the 4 group members worked an average of 5 hours per day on system development.
4. The average Embedded Systems Engineer hourly rate is $31.43.

Hence,

*DT = 4 * 84 days * 5 hours/day*

DT = 1,680 hours

$R = \$31.43/hour$
$NRE = 1{,}680\ hours * \$31.43/hour$
$NRE = \$52{,}802.4$

Total Cost

The formula for total cost is as follows:

$$C_T = NRE + (RP * V)$$

Supposing that the WindTel System to be installed at the Civil Engineering's Wind Tunnel is the only unit to be produced, we have V = 1.

Therefore,
$C_T = \$52{,}802.4 + (\$176.69 * 1)$
$C_T = \$\ 52{,}979.09$

V. System Block Diagram

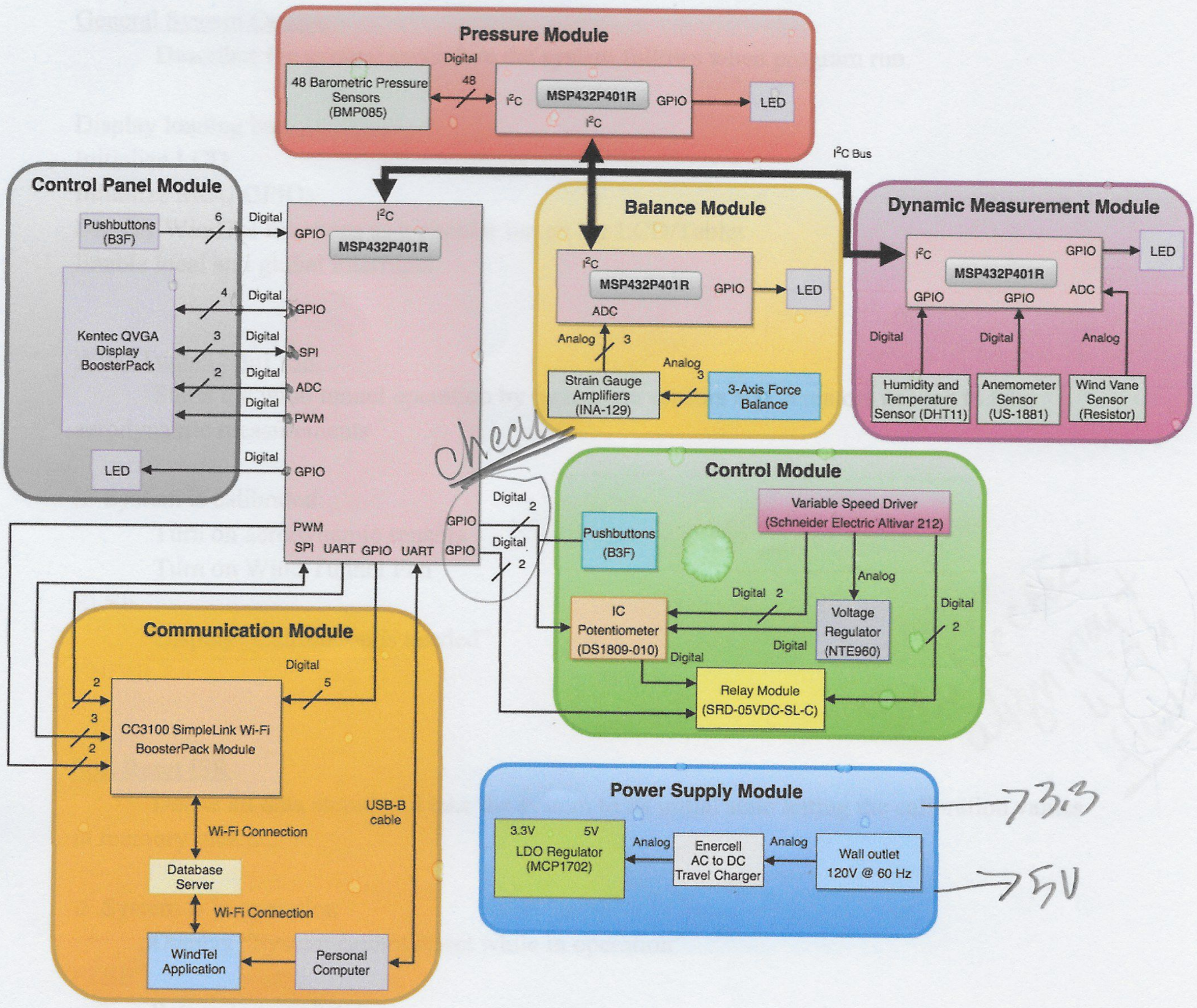


Fig. 5: Block Diagram Version 3

OK

VI. Detailed Software Plan

General System Outline

Describes the general procedure the system follows when program run.

Display loading bar
Initialize LCD
Initialize MCU GPIOs
Display WindTel functions as a circular list on the LCD/Tablet
Enable local and global interrupts

Wind Tunnel Start ISR

Starts the wind tunnel operation by turning on sensors and actuators needed to take aerodynamic measurements

IF System is calibrated
    Turn on aerodynamic sensors
    Turn on Wind Tunnel Fan
ELSE
    Display "Calibration is needed"
ENDIF

Doublecheck alignment with flowcharts

Soft Reset ISR

Delete all data stored and take the system to its initial state letting the calibration values in memory intact.

IF System is in operation
    Display "System cannot Reset while in operation"
ELSE
    Return to initial state
ENDIF

Calibration of the system ISR

The calibration option will communicate with the slave MCU and set the mechanical balance in a calibration status where an object of 0.01lbs will be placed inside the chamber so that the system will have a precision of at least a hundredth of a pound.

IF System is in operation
    Display "System cannot calibrate while in operation"
ELSE
    Store first calibration values (without object nor wind inside the tunnel)
    Turn on Wind Tunnel Fan
    Start wind speed check procedure
    Store second calibration values (with wind but without object)
    Prompt user to place object inside Wind Tunnel
    WHILE Object is not placed inside Wind Tunnel
        Prompt user to place object inside Wind Tunnel
    ENDWHILE
    Store third calibration values (with object and wind on)
ENDIF

<u>Wind Speed Check Function</u>

This function will set the Wind Tunnel fan to the desired speed.

WHILE Speed value is not in the acceptable range (within value + threshold)
    Verify Wind Speed measure from Anemometer
ENDWHILE
Initiate Counter
WHILE Counter < Counter limit
    Verify Wind Speed
    IF Wind Speed has not gone over or under threshold value
        Increase Counter
    ELSE
        Restart Procedure
    ENDIF
ENDWHILE

<u>Shutdown ISR</u>

The shutdown operation will stop the data acquiring process, save the data locally in a computer and turn-off the power of the wind tunnel.

IF System is in operation
    Display "System cannot shutdown while the Wind Tunnel is

not in operation"

ELSE

Turn-off aerodynamic sensors

Turn-off Wind Tunnel Fan

ENDIF

Data Acquisition ISR

This function will acquire data from the experiment being processed in the Wind Tunnel and save it in the computer.

IF System is in operation

Collect data from experiment

Display aerodynamic measurements in the Metric System and the English System units

Store experiment data in computer

Prompt user to end data acquisition process

WHILE Data acquisition process has not ended

Prompt user to end data acquisition process

ENDWHILE

ELSE

Display "System cannot acquire data while Wind Tunnel is not operating"

ENDIF

Diagnostic ISR

The diagnostic option shows the status of the wind tunnel, latest update and calibration information.

Retrieve last experiment data

Display last experiment data in Tablet/LCD

Display current software version

Display calibration parameters

VII. References

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Wind Tunnel Automation Using Embedded System Technologies

Wind tunnels are used to study the aerodynamics of cars, boats, aircrafts and other objects by moving air through a chamber and analyzing its effects on the object. In 2013, a team of students from the ICOM-5217 course of the University of Puerto Rico at Mayagüez (UPRM) designed a system capable of taking measurements of force, pressure and velocity upon the object being studied using the wind tunnel of the Department of Civil Engineering managed by Dr. Raúl Zapata. However, the system had a restriction: the software could only be accessed using an Android tablet. After a few years, the tablet software became obsolete and various hardware components were damaged, making the tunnel useless.

WindTel is proposed as the solution of the aforementioned problems. This system measures telemetry data and sends it to any device that contains the WindTel application. In addition, sustainability, extensibility, and modularity—both in terms of software and hardware—is emphasized throughout the entire design process to make the system fruitful for academic and industrial use in the future.

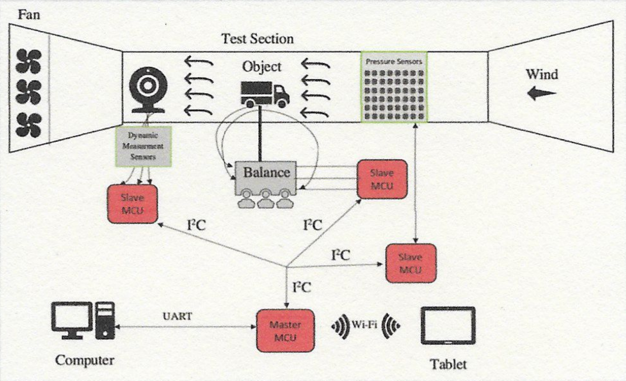

Figure 1: WindTel Global View

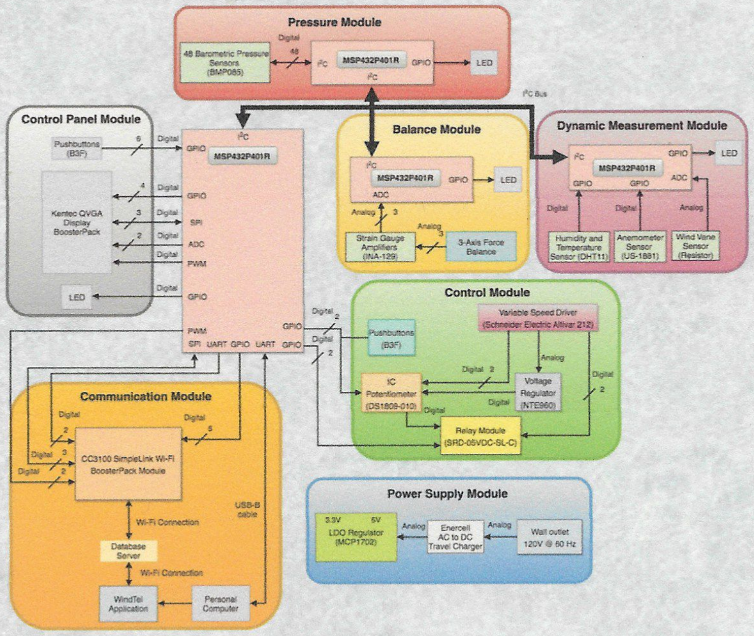

Figure 2: WindTel Block Diagram

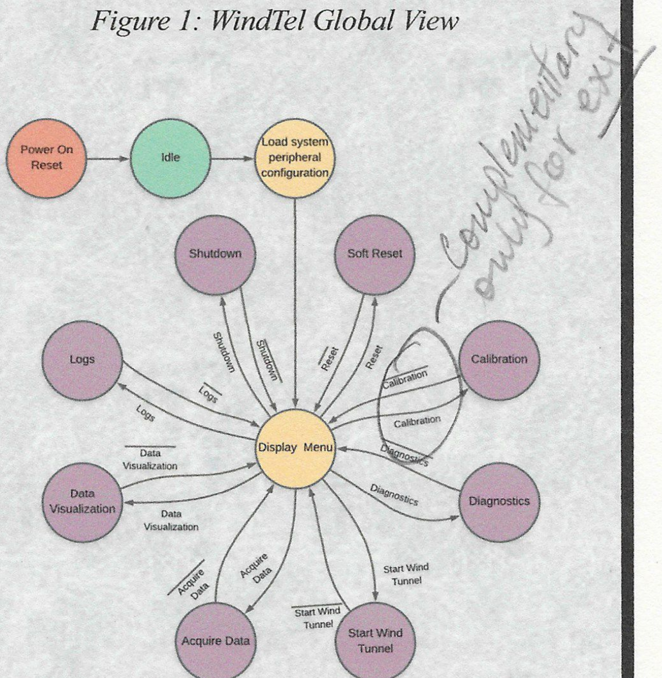

Figure 3: WindTel System State Diagram

Participating Students:

Nelson G. Rodriguez Ortiz | Luis O. Vega Maisonet | Kahlil J. Fonseca Garcia | Misael Valentin Feliciano