Report for Prototype of an affordable inserted ventilator Tube Flow meter

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Abstract

We present a prototype for a bidirectional ventilator flow meter based on Bernoulli's principle to be used in a medical setting to monitor the gas flow between a mechanical ventilator and an intubated patient. Our design facilitates sharing of a ventilator among several patients, each of whom are separately monitored using flow meters with access to individual patient records.
Our prototype consists of a flow tube with pressure sensors wirelessly connected to a PCB board capable of data acquisition, local data storage on an SD card, patient record display and transmission over a wireless network or through radio to a base station.

Need for the Device

The Covid-19 pandemic brought about a critical scarcity of ventilator machines for intubated patients in many countries including the United States, and this scarcity was far more serious in the developing world: for example, in early 2020 the Liberian Public Health Institute's Director of the Infectious Diseases and Epidemiology Department stated that "there is just one ventilator in the country, located at a hospital outside of the capital…"[1] This shortage highlighted a glaring vulnerability in global healthcare infrastructure, prompting a pressing need for proactive measures to address such challenges in the face of future pandemics. The magnitude of the loss of life and property during the Covid-19 crisis underscores the urgency of developing comprehensive strategies and bolstering resources to better prepare healthcare systems for potential future outbreaks.

Amidst the shortage of ventilators, a pragmatic solution which gained traction during the pandemic involves the shared use of a single ventilator among multiple patients. This approach is increasingly recognized as a feasible means of mitigating the scarcity of ventilators, thereby saving more cost and ultimately more lives. For instance, in February 2021 the U.S. Food and Drug Administration posted "Using Ventilator Splitters During the COVID-19 Pandemic - Letter to Health Care Providers," authorizing the use of ventilator splitters for healthcare facilities.[2]

Recognizing that patients exhibit varying degrees of airflow requirements, implementation of effective, real-time airflow monitoring is badly needed. However, there exists a market vacuum for effective, affordable and convenient airflow monitors for ventilator sharing:

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[1] Josh Holder, "Tracking Coronavirus Vaccinations Around the World," *New York Times*, November 29, 2021. "(https://www.nytimes.com/interactive/2021/world/covid-vaccinations-tracker.html)

[2] U.S. Food and Drug Administration, "Using Ventilator Splitters During the COVID-19 Pandemic - Letter to Health Care Providers," February 9, 2021. (https://www.fda.gov/medical-devices/letters-health-care-providers/using-ventilator-splitters-during-covid-19-pandemic-letter-health-care-providers)

for example, the FDA's EUA list of accessories includes only one flow monitor, the "PEEP-Alert Pressure and Flow Monitor," which, according to its manufacturer, reports the pressure and flow rate averaged over three-second intervals with an accuracy of 10% - 15% depending on conditions, shows its readings on a display built into its case instead of uploading to a local server, and has a price of $390[3].

Hence our enhanced ventilator flow meter designed for optimal performance. This device boasts the capability to seamlessly monitor airflow rates within ventilator tubes, with a LCD screen providing real-time data as well as line plots illustrating historical airflow rates. Furthermore, it accurately timestamps and compiles this data, which in turn can be saved to a micro SD card with a convenient micro SD card feature integrated into the LCD display. The user can also upload data to an online server via a private IP address, leveraging improved integration into hospital wireless networks. This ensures real-time, remote, and dependable respiratory monitoring, enhancing overall patient care.

Background Physics

Fluid flow and the Bernoulli Equation

The behaviors of fluids are well described by the continuity, Navier-Stokes, and Bernoulli equations as long as a number of approximations are applicable. In our case, flow velocities are small compared to the speed of sound, while variations in pressure inside the device are at most a few percent of atmospheric pressure, which means that the device can be

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[3] PEEP-Alert Pressure and Flow Monitor web site, (https://www.peep-alert.com/products/peep-alert)

seen as several parts with respective constant pressures. Therefore we can approximate two velocity-dependent pressures with the Bernoulli Equation:

$$P_1 + 1/2\rho_1 v_1^2 + \rho_1 g h_1 = P_2 + 1/2\rho_2 v_2^2 + \rho_2 g h_2$$

where *P* is pressure, *r* is density, *v* is fluid velocity, and *h* is height. Since the change in pressure inside our device will be negligible, $\rho_1 \approx \rho_2$. Assuming the flow is horizontal so that $h_1 = h_2$, we have

$$P_1 - P_2 \approx 1/2\rho(v_2^2 - v_1^2)$$

Effecting a fluid flow of *Q* cubic meters per second through a tube with cross sectional area *A* square meters requires a flow velocity (in meters per second) of

$$v = Q/A$$

An inspiratory flow rate of 30 liters/minute corresponds to $Q = 5\times10^{-4} m^3/s$. This flow, passing through a tube with cross sectional area $2280mm^2$ ($0.00228m^2$) would yield a flow velocity of 0.219m/s, while an area of $600mm^2$ would produce a flow velocity of 0.833m/s. Double the flow rate to 60 liters/minute would double the flow velocities to 0.438m/s and 1.666m/s.

In tests of the first version of our device we pumped air through a tube whose cross-sectional area was $2280mm^2$(38mm*60mm) at the inlet, narrowing to $600mm^2$ (10mm*60mm) in the tube's center. From the Bernoulli Equation, we expect (for *Q*=0.5 liters/second, corresponding to 30 liters/minute) the pressure difference between these two regions of the tube to be 0.388Pa assuming that the atmospheric density at sea level is about 1.2 kg/m^3. For Q=1 liter/second we calculate $\Delta P \approx 1.550$Pa.

In a clinical setting we would determine the airflow through the device by measuring the pressure difference between the inlet and central region of the flow tube with DPS310 pressure sensors. These are manufactured by Infineon Technologies AG and mounted onto small "breakout boards" (and sold) by Adafruit Industries LLC.

Turbulent flow

The Bernoulli equation applies to fluids undergoing laminar flow, but it doesn't apply to turbulent flow. The Reynolds number of the fluid and the channel through which it passes can be used to determine whether a fluid will undergo turbulent flow. Systems with Reynolds number R_e less than 2,300 will usually exhibit laminar flow, while those with R_e greater than 2,900 will tend to show turbulence.[4]

For our system, the Reynolds number is

$$R_e = u d_h / v$$

where u is the fluid's velocity, d_h is the "hydraulic diameter" of the flow tube, and v is the "kinematic viscosity" of air. $v=1.506*10^{-5}m^2/s^5$ at 20°C, and for a rectangular pipe $d_h=4A/C$. Our two cross sections will yield Reynolds numbers of R_e=950.108 and R_e=2578.864 respectively, suggesting that the air flow in our device is laminar, not turbulent, when Q = 0.5liters/second (30

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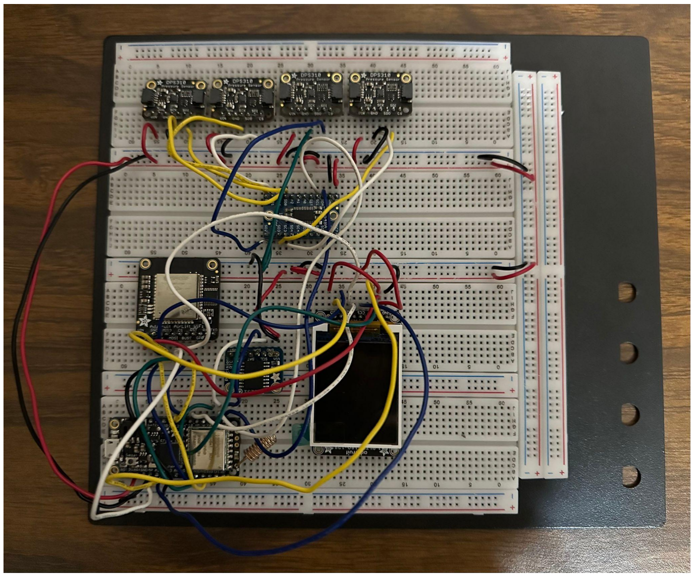
[4] https://en.wikipedia.org/wiki/Reynolds_number, visited November 14, 2023.

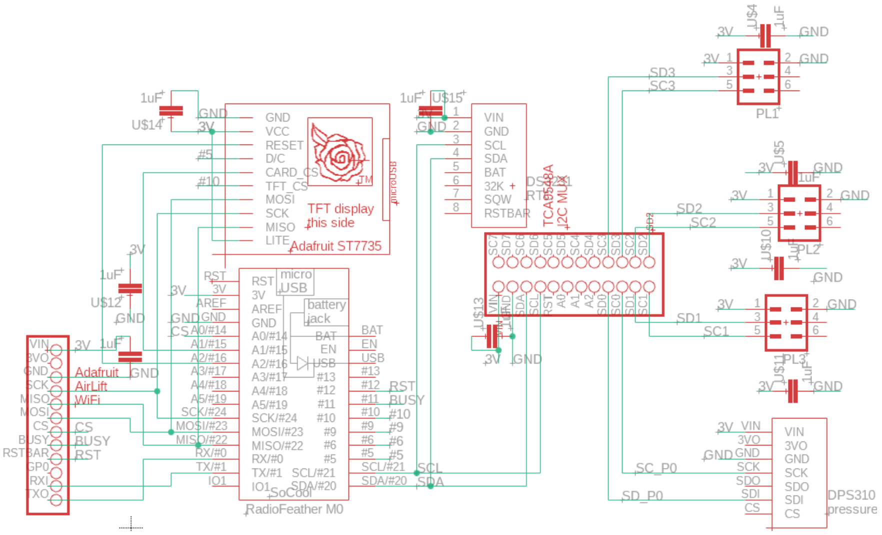
[5] https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html, visited November 14, 2023.

liters/minute). Note that doubling the flow will double the Reynolds number, perhaps resulting in turbulent flow in the device.

Prototype Device

The current prototype is a testing board containing the minimum necessary hardware to record, display, and communicate data to another data storage device. It has no flow meter structure around the DPS310 sensors and has not been tested in a situation that would accurately assess its ability to perform its task.





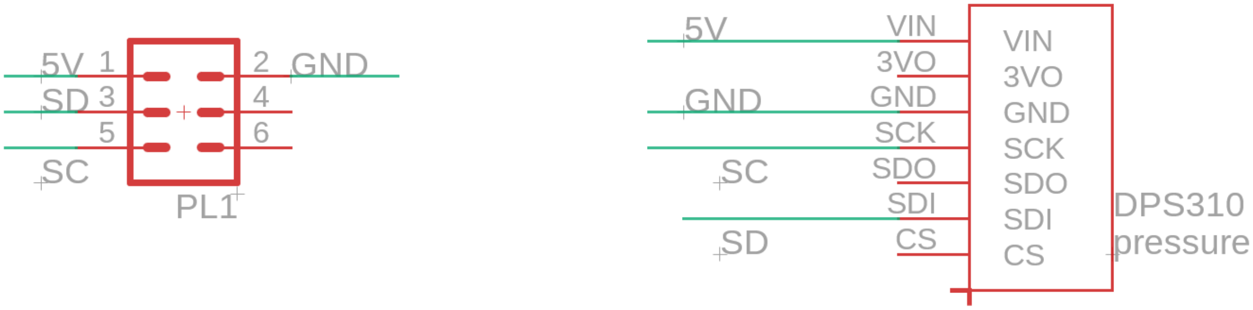


Fig 1. The prototype board with home board and sensor board schematic. The prototype board is equivalent to 1 home board plus 3 sensor boards except all 1µF capacitors.

The Prototype that will be used to gather actual data is a 3D printed structure that is effectively a rectangular box with a lowered section in the middle made out of PLA attached to sensors and the rest of our hardware. This utilizes the Bernoulli equation to cause an increased air flow in that area, altering the pressure there. This pressure is read by 3 DPS310 pressure sensor devices, which record the raw pressure data and feed it into the software program in the electronics of the device. The resulting airflow across each sensor is then calculated

The 3D printed structure is made from PLA[6], a monomer made from fermented plant starch with a melting point 130-180 °C.An alternative is a more rigid PETG plastic if a more rigid form is desired[7]. The box is made with one side as a separate lid to prevent issues with 3D printing hollow objects. The 3 sensors on 3 separate circuit boards will be exposed to the air flow via 3 large holes in the bottom of the flowmeter structure. These will be sealed by EPDM o-rings, which will be pressured into sealing by 6 screws pressed into the screw holes of the sensor board and structure.

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[6] https://en.wikipedia.org/wiki/Polylactic_acid visited 11/13/ 2023

[7] https://en.wikipedia.org/wiki/Polyethylene_terephthalate visited 11/13/2023

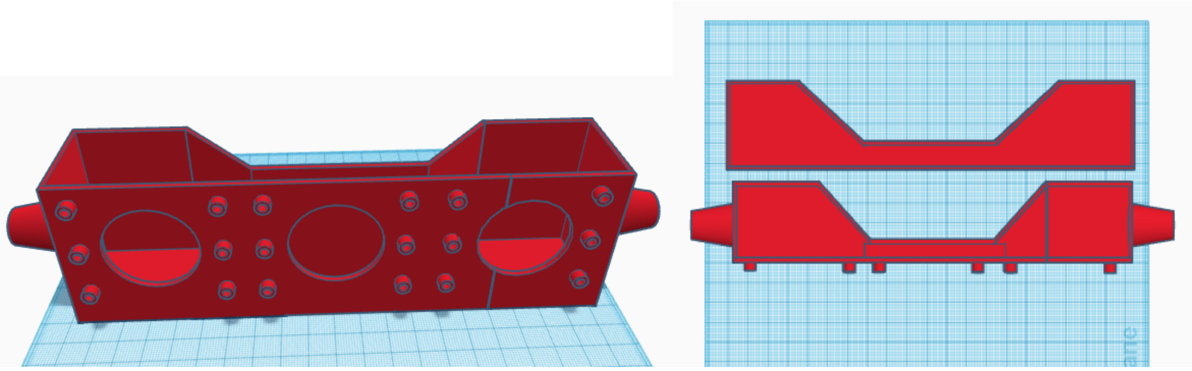

Fig 2. Main flow meter structure with lid as one side, holes for sensors and screw based securing structure on the bottom.

Hardware

The most important piece of hardware is the DPS 310 sensor, manufactured by Infineon. The sensor has a relative accuracy and relative precision of 6 Pa and .2 Pa for out of the box components[8]. The accuracy is equivalent to 60 cm at sea level , thus a very accurate sensor as that atmospheric distance is quite small. The precision is thus 2cm of atmospheric height. This is an even more important feature as it practically guarantees that pressure differences that are observed in the sensors are real and not a result of device error.

The devices are also temperature sensitive, with the device having a specific sensitivity of .5 Pa/K[9]. If we had to need to for the prototype or for coding the final project, it would be wise to input values into its calibration coefficient. We have not as of yet tried to this as so far all of our raw data reading has been from the classroom in which we were working on the project.

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[8] https://www.infineon.com/cms/en/product/sensor/pressure-sensors/pressure-sensors-for-iot/dps310/, visited 11/13/2023

[9] https://www.infineon.com/dgdl/Infineon-DPS310-DataSheet-v01_02-EN.pdf, visited 11/13/23

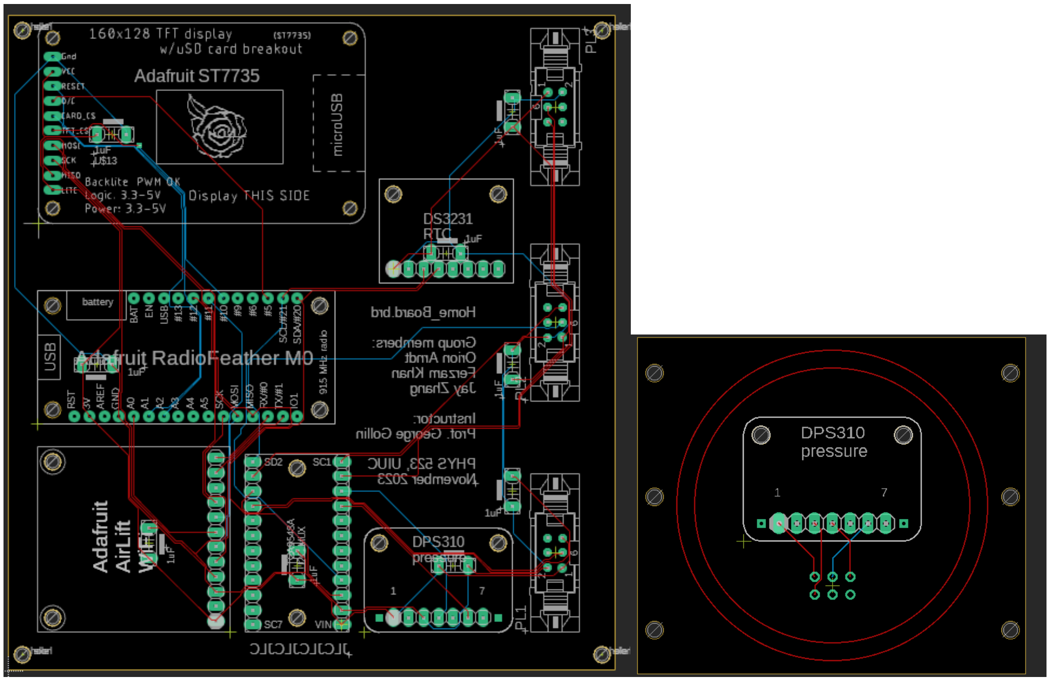

Fig 3. Snip of BRD file of PCB for both the home and sensors from EAGLE

The other devices are the Radio Feather M0, the DS3231 clock, Adafruit Airlift Wifi, I2C multiplexer, Adafruit ST7735 TFT display, capacitors and ribbon head connectors. The radio feather acts as the mother board here, as all devices are directly or indirectly connected back to it. It also enables radio communication which may have some future uses. The clock aids the sensors in marking time in sync, as being out of sync would give erroneous measurements. The Airlift Wifi is necessary to send the prototype testing data to a retrievable storage, and will be necessary in the final product to send information to the ventilator system within the hospital networks. The I2C multiplexer allows 4 or more sensors to send information to the radio feather. This would otherwise not be possible, as a quirk of I2C devices is that multiple devices of the same part cannot be all plugged into the I2C ports. The TFT display allows us and in the future hospital staff to easily see the pressure and flow rates present in real time without using the serial monitor in Arduino, which will be explained in the software section. The capacitors reduce voltage fluctuation, which can slightly alter the function of the hardware. The ribbon connectors are for the ribbon cables connected to the sensor boards so that they can flexibly be attached to the structure and the device can be more freely manipulated when attached to a flow tube.

Software

We program the M0 using the Arduino Integrated Developers Environment (IDE), an open-source IDE with well documented and supported libraries for microprocessor communication, sensor detection, and wireless communication. For offline data analysis, we use Python.

The main purpose of our Arduino IDE code is to set up the hardware, calibrate the DPS 310 sensors, perform the DAQ routine, perform local routines for storing data locally to an SD card and displaying data on the TFT display, and transmitting data over wireless communication and radio. For wireless communication, which is the project priority for successful integration of our prototype in a medical setting, we use the capabilities offered by the WiFiNINA library.

Data and Analysis

Data Acquisition

Our data acquisition method is executed within the Arduino IDE code. We take some initial readings to calculate the mean and square mean values in the setup for correcting our measurements. Our prototype continuously takes readings and performs pressure corrections while the program is running. We store the required readings locally on an SD card and display the data on the TFT display. Since the readings are no more than 200 bytes per reading, taking ~10 seconds per reading, a 16 GB microSD card will last a few years at least, even with storing more data than we are currently storing.

Calibration:

We perform pressure calibration in our setup to remove any biases and offsets from individual sensors by taking an initial 10 readings and calculating the mean and square mean of individual pressures and the pressure differences for all DPS 310 sensors. We then subtract the difference of average readings from the pressure difference between two sensors (uncorrected readings) to get the corrected readings. Figure 4 depicts our calibration results for DPS 310 sensors on the same height level, correcting any baseline offsets to be mostly within ± 2 Pa.

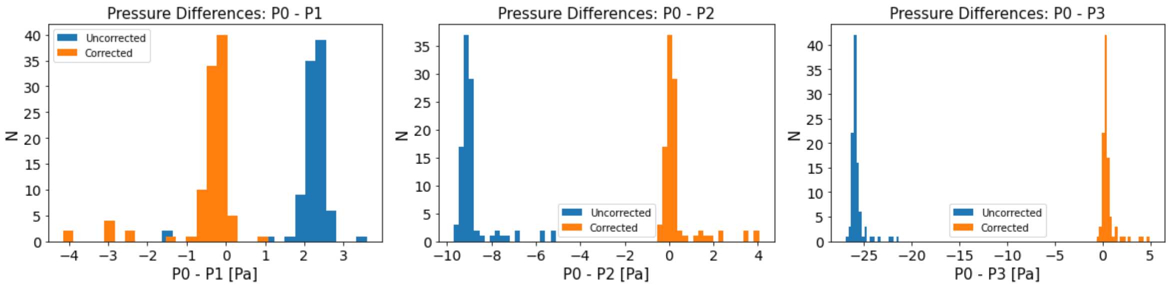

Fig 4. Histograms for uncorrected (blue) and corrected (orange) pressure differences [Pa] (a) P0-P1, (b) P0-P2, (c) P0-P3

Data Transmission

We use the IEEE 802.11 internet protocol to transmit data over a wireless network to the client (medical personnel in a hospital or at Carle Illinois College of Medicine). The client can send an http request to a specified IP address (for the Airlift) and a serial port. The Airlift listens to available clients and once it identifies a connection, it can transmit the requested data over wifi as an http reply on a webpage. Our current software structure is able to send simple data in real time like raw readings and some simple analyzed data. Our goal is to be able to send data specific to a request type both in raw form of sensor readings, and advanced form of graphs and plots, over the period of requested time. This will require smart and efficient data allocation and storage, with capability to delete previous data after a certain amount of time to avoid memory overflow.

Initial Analysis

Our prototype can successfully estimate pressure and temperature for a stable atmosphere and turbulent fluid flow. Figure 5 depicts the pressure values of the individual DPS 310 sensors over time for 100 readings. For the first 10 readings, we simulated a turbulent air flow from blowing air near the sensors, and successfully captured a turbulent pressure reading which quickly settled into laminar flow.

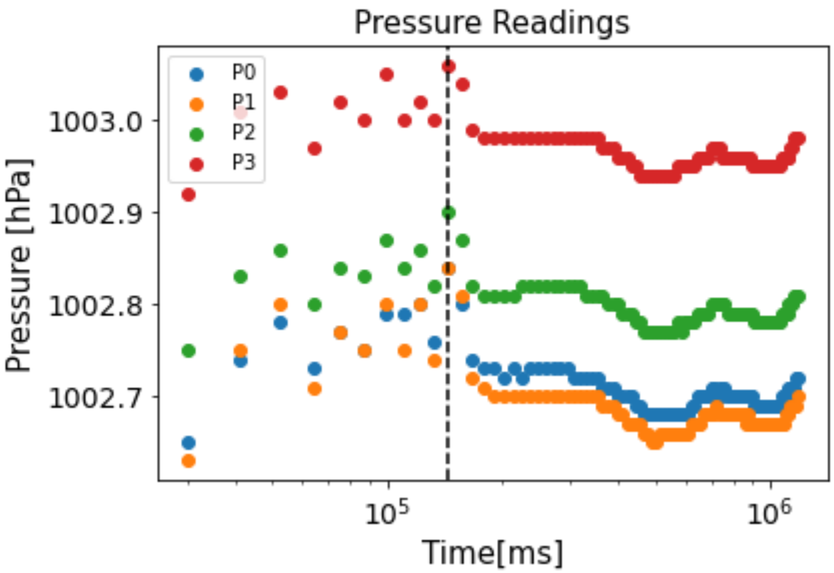

Fig 5. Pressure readings [hPa] from DPS 310 sensors P1, P2, P3 and P4 over time [ms] for 100 readings. The first ~10 represent turbulent flow from air blowing close to the sensors.

Once our flow meter prototype is complete, we plan to perform analysis to compare our calibration for pressure differences to the theoretical value of pressure differences from Bernoulli's equation. We also plan to test our prototype's pressure difference versus fluid flow rate and compare our results with a previous prototype designed by Gollin et al. (2022).

Future Goals and Possible Problems

The first immediate goal for the end of the semester is to order the PCBs and assemble them with the flowmeter structure. Then we will be able to test the flow meter when integrated into a flow tube that will regularly flow air through it and test the results versus the prototype that Professor Gollin made before us to test its functionality. We will also want to expand on the graphing and communication abilities of the flowmeter, more specifically the ability to send specific requests rather than boolean requests.

For the next semester we wanted to do more extensive prototype testing and analyze the data for faults in our coding, hardware or flowmeter structure. We will also want to integrate our testing with Carle Illinois College of Medicine, as geeting testing with air flows that more accurately mimic lungs and breathing will be important for testing accuracy, and to test with different tub geometries. Further we will also want to secure a patent for this device so that others do not recreate and steal our work.

There are still some possible problems on the horizon that we need to consider. For example, we need to take the compilation of our device into ventilator tubes into account, which may fail due to size difference, unreliable connection, etc. We also need to consider the possibly huge cost of mass production of PCB boards, 3D models and related components, and local data storage management is also worth noticing for future development.

Conclusions

The current prototype is able to successfully perform data acquisition using the I2C protocol from a flow tube with DPS 310 pressure sensors, and transmit data via radio or through wifi to a remote client (target personnel in a medical setting). We are able to successfully calibrate our DPS 310 sensors for pressure readings, and in the future with a flow tube will be able to monitor the air flow in the flow meter for a patient. The complete prototype will be able to facilitate ventilator sharing between several patients with individual air flow monitoring through the flow meter.