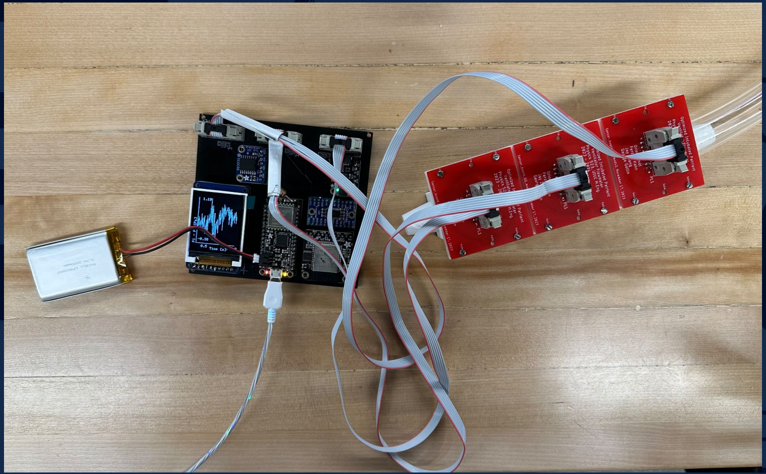
Prototype of a Ventilator Tube Flow Meter



Orion Arndt

Ferzem Khan

Jay Zhang

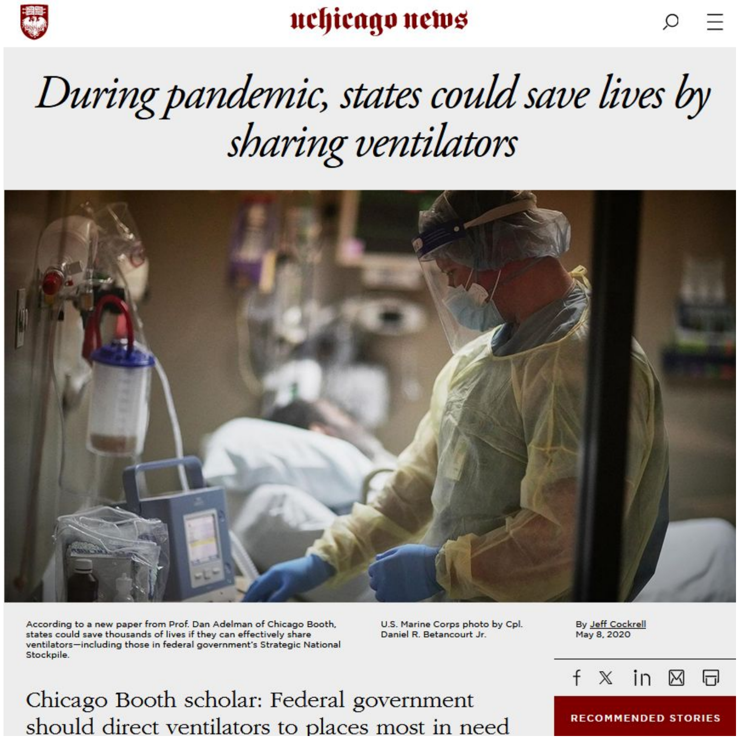
PHYS 523 Final Presentation | April 30 2024

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Introduction

- Severe shortage of ventilator machines during Covid-19 pandemic
- Prepare for the next global pandemic
- Ventilator sharing saves money and life*

*U.S. Food and Drug Administration, "Using Ventilator Splitters During the COVID-19 Pandemic - Letter to Health Care Providers," February 9, 2021.



uchicago news

During pandemic, states could save lives by sharing ventilators

According to a new paper from Prof. Dan Adelman of Chicago Booth, states could save thousands of lives if they can effectively share ventilators—including those in federal government's Strategic National Stockpile.

U.S. Marine Corps photo by Cpl. Daniel R. Betancourt Jr.

By Jeff Cockrell
May 8, 2020

Chicago Booth scholar: Federal government should direct ventilators to places most in need

RECOMMENDED STORIES

https://news.uchicago.edu/story/during-pandemic-states-could-save-lives-sharing-ventilators

Introduction (cont'd)

- Varying degrees of airflow necessitates effective airflow monitoring
- Market vacuum of effective and affordable airflow monitors; e.g. the "PEEP-Alert PAA-0005 Pressure and Flow Monitor" costs $458.84

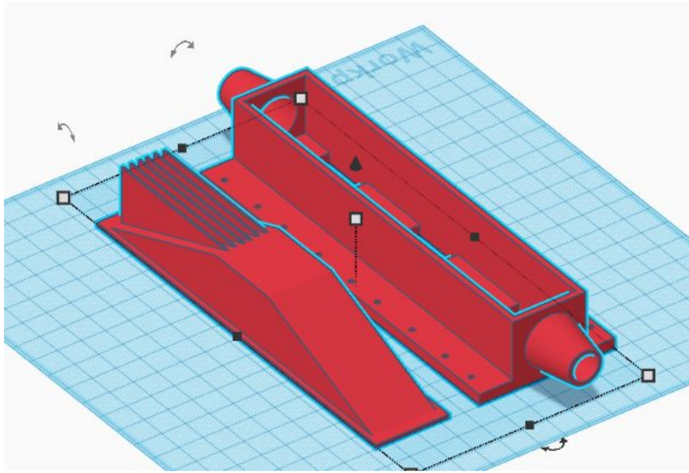
https://www.amronintl.com/peep-alert-pressure-and-flow-monitor-paa-0005.html

Our Solution

An optimized ventilator flow meter inspired by Prof. Gollin's prototype*.

- Monitor airflow rates in ventilator tubes;
- Display real-time airflow rates;
- Read time and compile it with airflow data;
- Store data locally to a micro SD card;
- Upload data to an online server via a hospital wireless network.

*Gollin, George, et al. An Inexpensive Ventilator Tube Insertion Flowmeter, 24 Feb. 2022. (Unpublished)



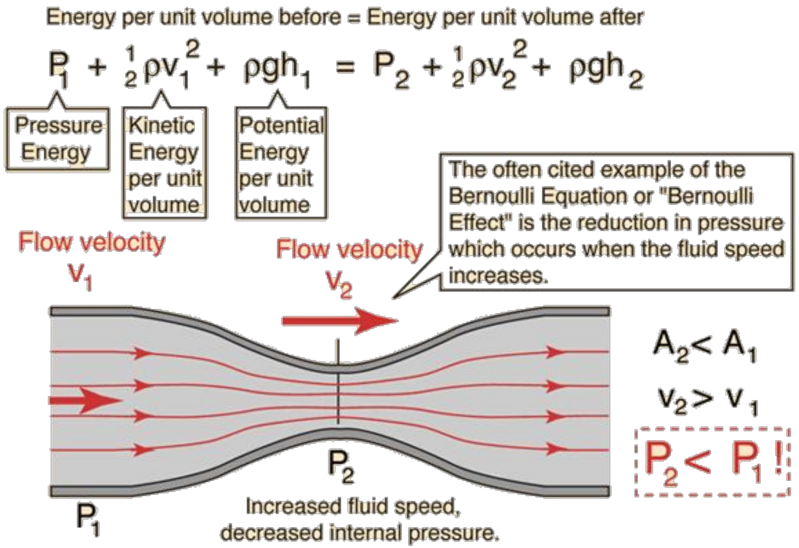
One of our 3D designs made in TinkerCAD

Fluid Flow and Bernoulli's Equation

$$P_1 + \frac{\rho_1 u_1^2}{2} + \rho_1 g h_1 = P_2 + \frac{\rho_2 u_2^2}{2} + \rho_2 g h_2$$

$$\rho_1 = \rho_2,\ h_1 \approx h_2,\ so\ P_1 - P_2 \approx \frac{\rho(u_2^2 - u_1^2)}{2}$$

$$u = \frac{Q}{A}$$



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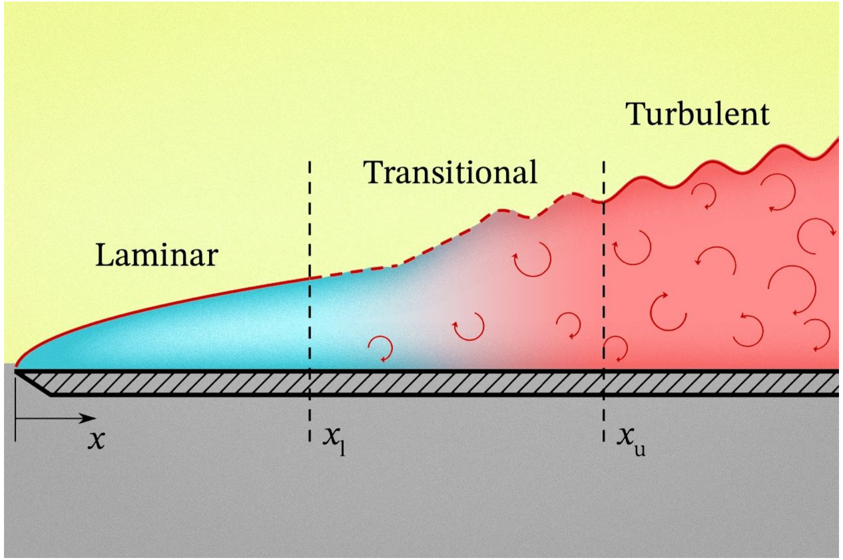
Turbulent Flow

- Bernoulli's equation applies to fluids undergoing laminar flow, not turbulent flow. Reynold's number estimates which type the flow would be:
  - R_e<2300: usually laminar flow;
  - R_e>2900: usually turbulent flow.

$$R_e = \frac{u d_h}{\nu}, \; where \; d_h = \frac{4A}{C}$$

- **ν**=1.506*10^{-5} m^2/s at 20°C



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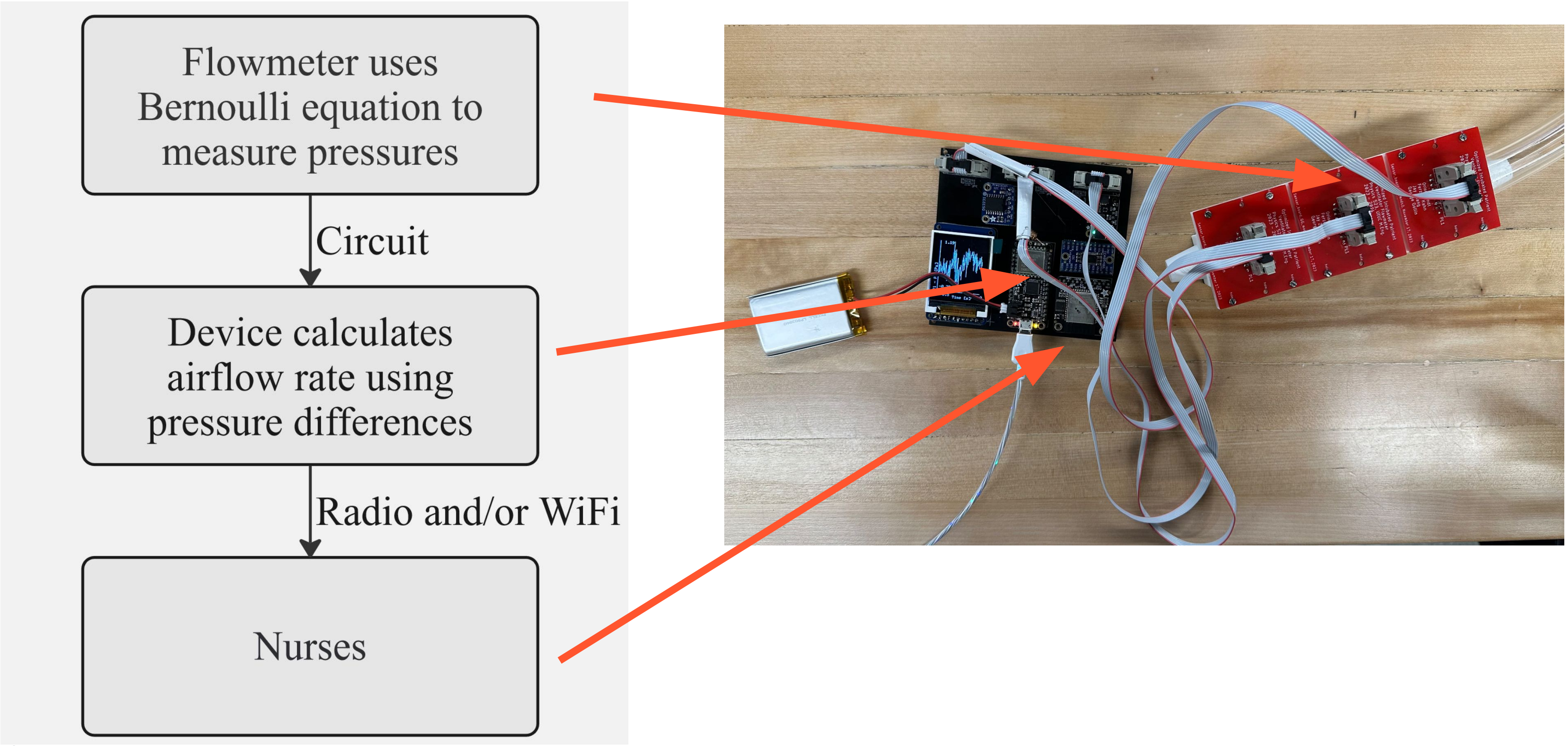
The Functional Process

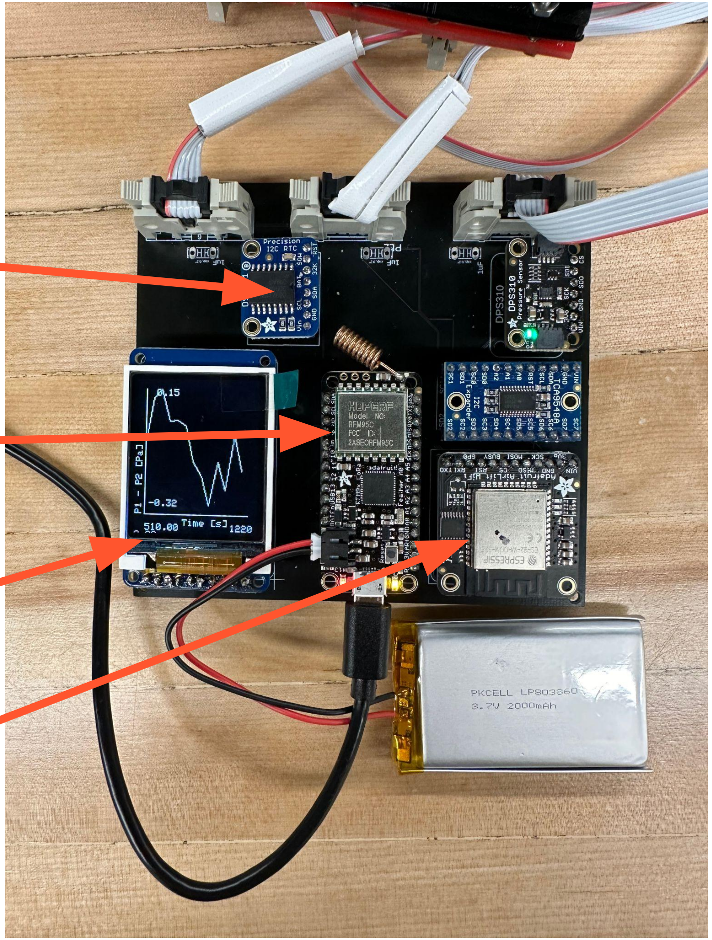


Roles

Orion Arndt	Jay Zhang	Ferzem Khan
Designing 3D model Creating sensor board	Creating home board (main circuit) Research and documentation	Data acquisition and transmission Data analysis

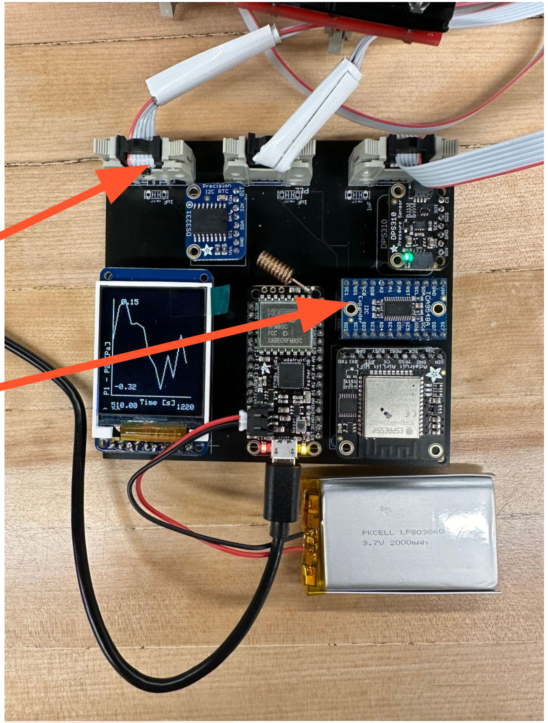
Hardware

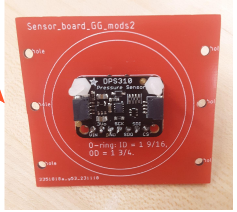
- DS3231 clock: used for time tracking within the programming.
- Adafruit Radio Feather M0: inter device communication, can use radio signals.
- Adafruit ST7735 TFT display: live visual and micro SD port
- Adafruit Airlift Wifi: wireless internet communication and encryption capabilities

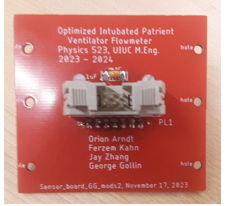


Hardware (cont'd)

- Capacitors: low pass filter
- Ribbon cable connectors on both the central and sensor boards.
- I2C multiplexer: without which multiple of the same I2C devices cannot be read.
- DPS310 pressure sensors: high accuracy, precision and frequency.
  - One on central board
  - Three on sensor boards, which are in the flowmeter







Cost Breakdown

- ~~None - Thanks George!~~
- Well, actually…*

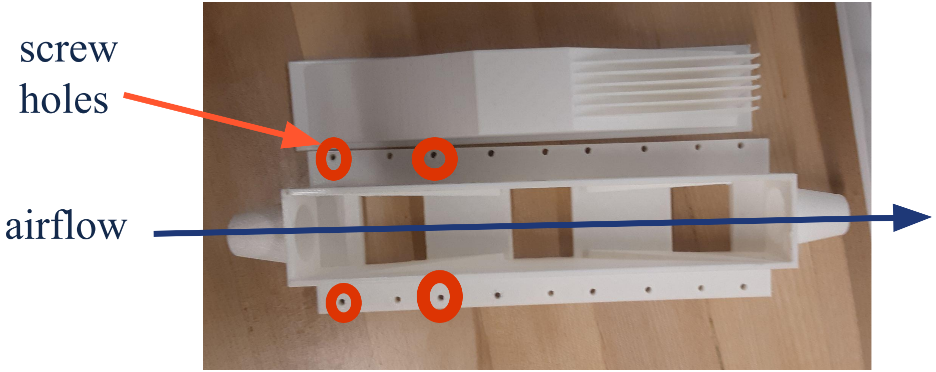
Adafruit Feather M0 microcontroller with RFM95 LoRa Radio	1	$27.96	Adafruit AirLift – ESP32 WiFi Co-Processor Breakout Board	1	$7.96
Adafruit DPS310 Pressure sensors	4	$22.24	Printed Circuit Board	4	$1.00
Adafruit DS3231 Precision RTC (real time clock) Breakout	1	$14.00	Ribbon cables (DigiKey # 1528-1925-ND)	3	$6.00
Adafruit 128*160 TFT display	1	$15.96	Adafruit TCA9548A I2C multiplexer	1	$5.56
Lithium-ion battery, 3.7V, 2000mAh	1	$11.25	Miscellaneous capacitors, connectors, etc.	1	$6.00
3D-printed flow tube	1	$3.00	**TOTAL**		**$120.93**

- Far cheaper than the $458 “PEEP-Alert Paa-0005 Pressure and Flow Monitor”

*assuming 100 pieces of each part are purchased; all prices for components are taken from the Adafruit website unless otherwise noted.

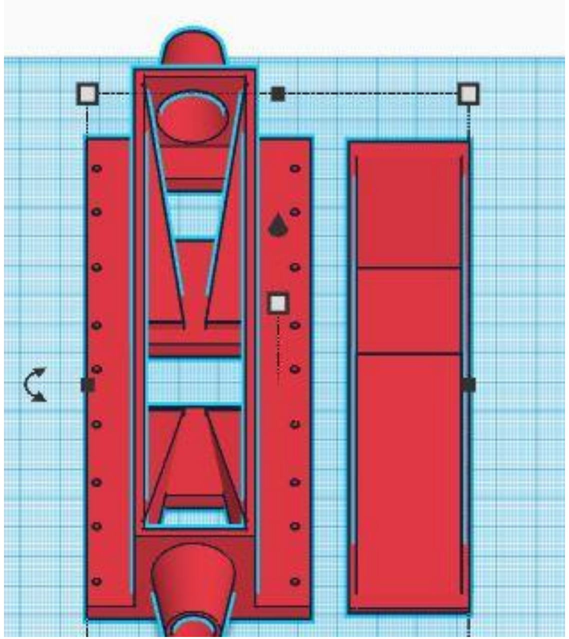
The Flow Meter Apparatus

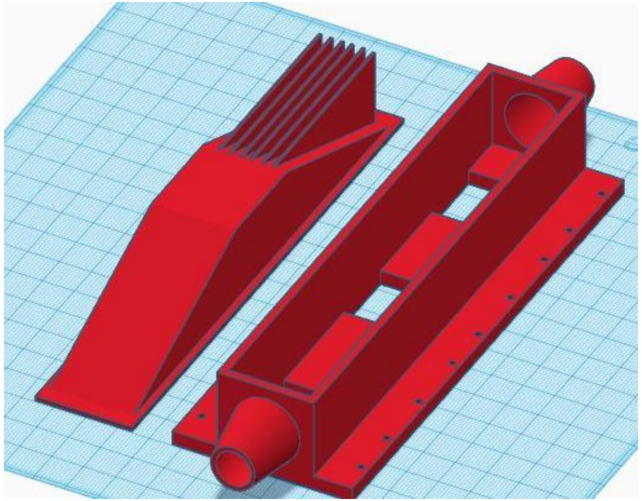
- Utilizes Bernoulli's equation by forcing air through a smaller cross-sectional area
- 3 DPS 310 pressure sensor boards sealed with o-rings and four screws. Six bends the PCB too much for a seal
- The material used to print the tube is PLA (Polylactic acid).

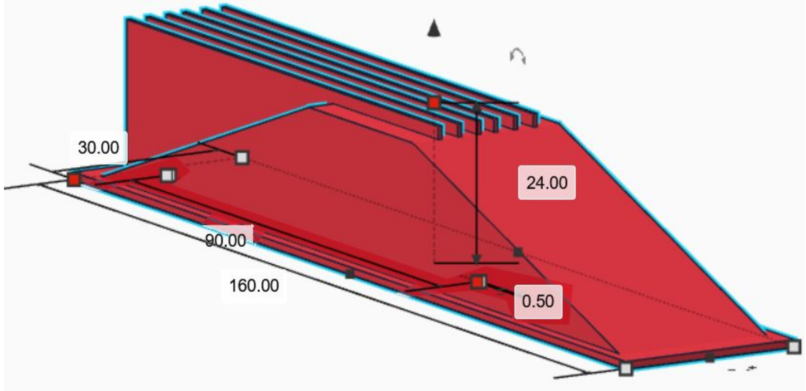


Flow Meter Geometries

- Flowmeter box interior is 26mm x 24 mm x 156mm
- Cones external are 20 mm long, 20mm large diameter and 10 mm small diameter







Flow Meter Geometries (cont'd)

PROTOTYPE	DESCRIPTION	CROSS-SECTIONAL AREA OF CENTRAL REGION	CIRCUMFERENCE OF CENTRAL REGION	REYNOLDS NUMBER for Q=0.5L/s
1	Small cross-sectional area in the middle, tapering	12 mm^2	16 mm	8322
2	Anti-turbulence fins over the outlet sensor, tapering	20 mm^2	42 mm	3162
3	Same as 2 but with fins over middle sensor as well	69 mm^2	52 mm	2554
4	Same as 3 but with larger cross-sectional area	207 mm^2	64 mm	2075

Software

Arduino IDE:

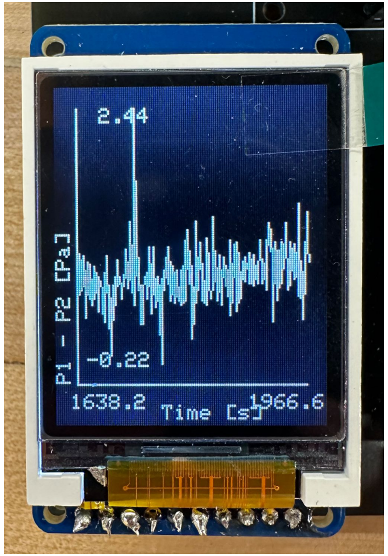
- Data collection and calibration from DPS 310 sensors
- Local storage on to microSD cards and display to TFT screen
- Transmission of data to hospital network via wifi - WiFiNINA

Python:

- Offline data analysis

Data Acquisition

- Calibration: During setup calculate average readings from each individual sensor (baselines), and corrected differences
- Read raw data from DPS 310 sensors, use calibration to get corrected readings
- Local storage to SD card, display to TFT, listen to Wifi client on server
- Data rate from flow meter ~ few hundred bytes per second
- Frequency of sensor reading: 1.02 Hz



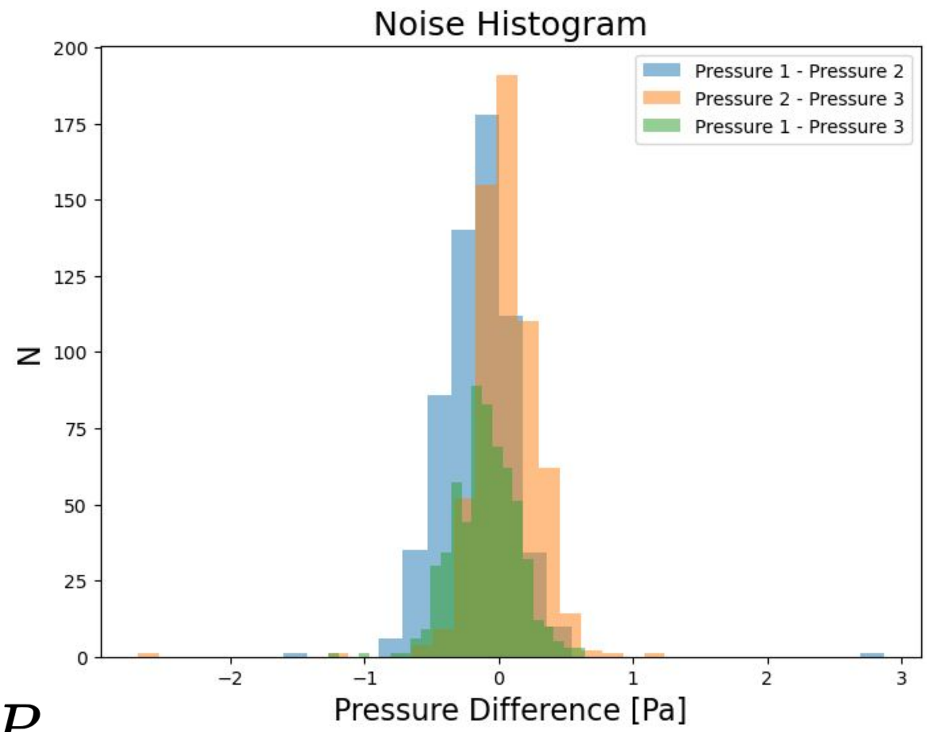
TFT display on home board

Calibration

DPS 310 Precision: 0.2 Pa (more precise than 9.8 Pa for PEEP-Alert)

DPS 310 Temperature Sensitivity: 0.5 Pa/K

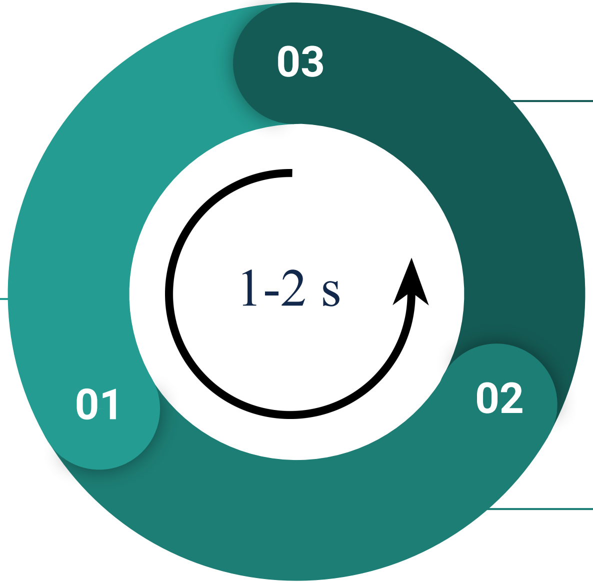
Fig. - Noise level DPS 310 sensors at the same height level, after correcting any baseline offsets is mostly within ± 1 Pa.



$$\Delta P_{corrected} = \Delta P_{uncorrected} - \Delta P_{avg}$$

Data Transmission

Client (local webpage) Request to Airlift's IP



Webpage takes information from server and displays it as real-time plot

Airlift checks sensor readings and gives http response to server

IEEE 802.11 wifi protocol (standard)
Capable of SSL/TSSL encryption

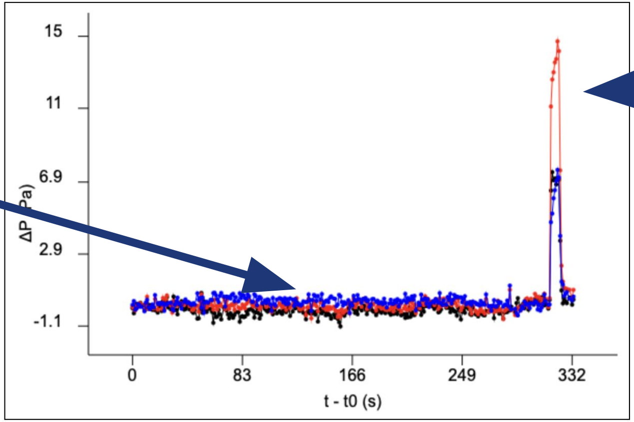
Data Transmission (cont’d)

No airflow - Stable

Airflow

Montoring Pressures in the Ventilator Flowmeter

○ Simulated data ◉ Real data



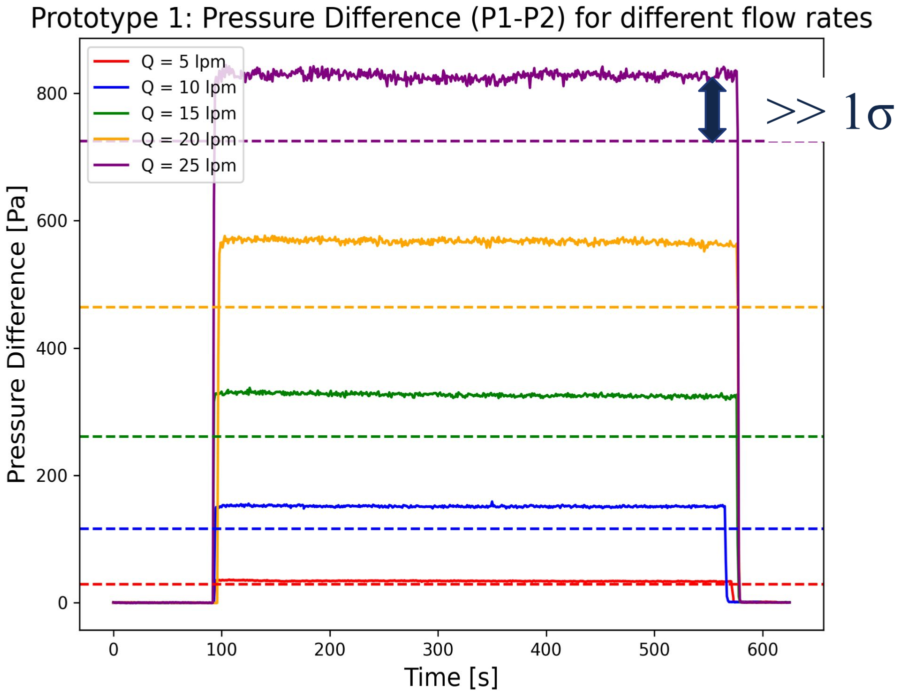
t0: Tue Apr 16 2024 15:51:20 GMT-0500 (Central Daylight Time)
Black: P1 - P2, Red: P1 - P3, Blue: P2 - P3

Number of points: 300

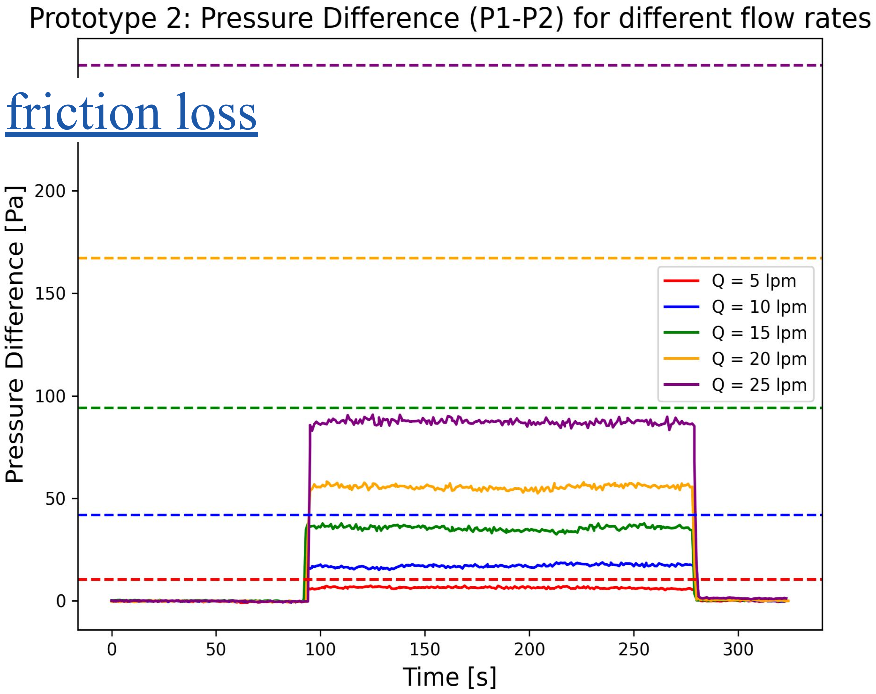
Latest time: Tue Apr 16 2024 15:56:53 GMT-0500 (Central Daylight Time)

Pressures recorded by the 4 sensors (Pa):
98090.73
98091.32
98090.95
98090.41

Pressure Difference between Inlet and Middle Sensor

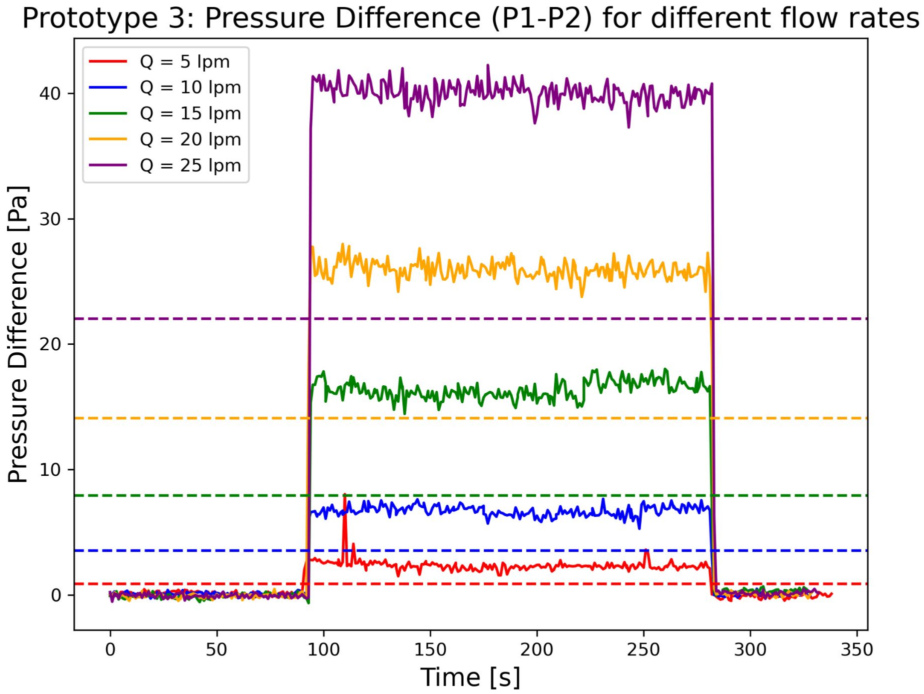


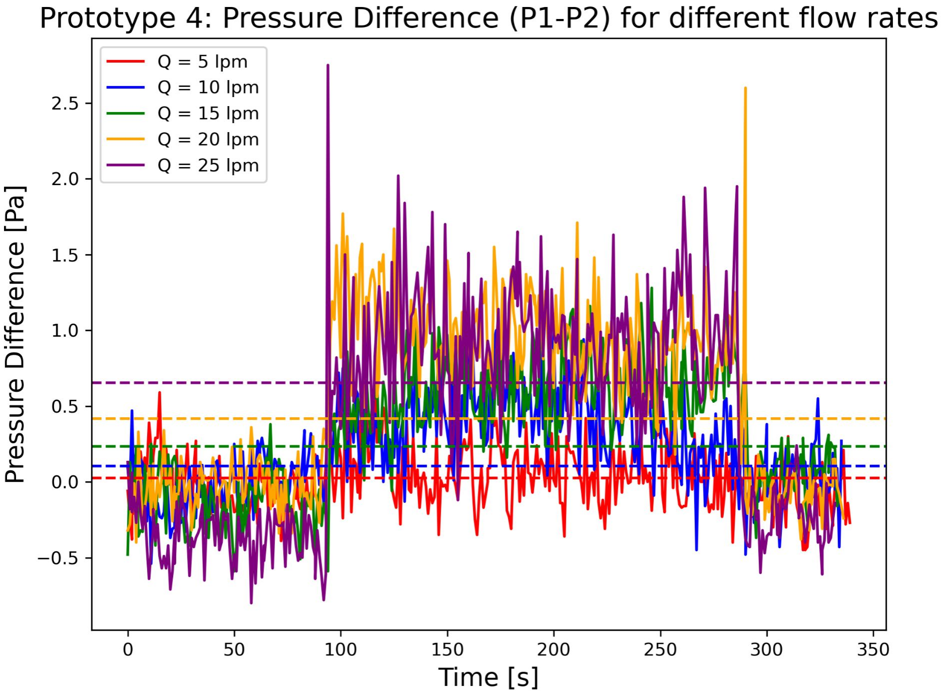
>> 1σ or friction loss



Dashed lines represent the theoretical values from Bernoulli's Equation.

Pressure Difference between Inlet and Middle Sensor



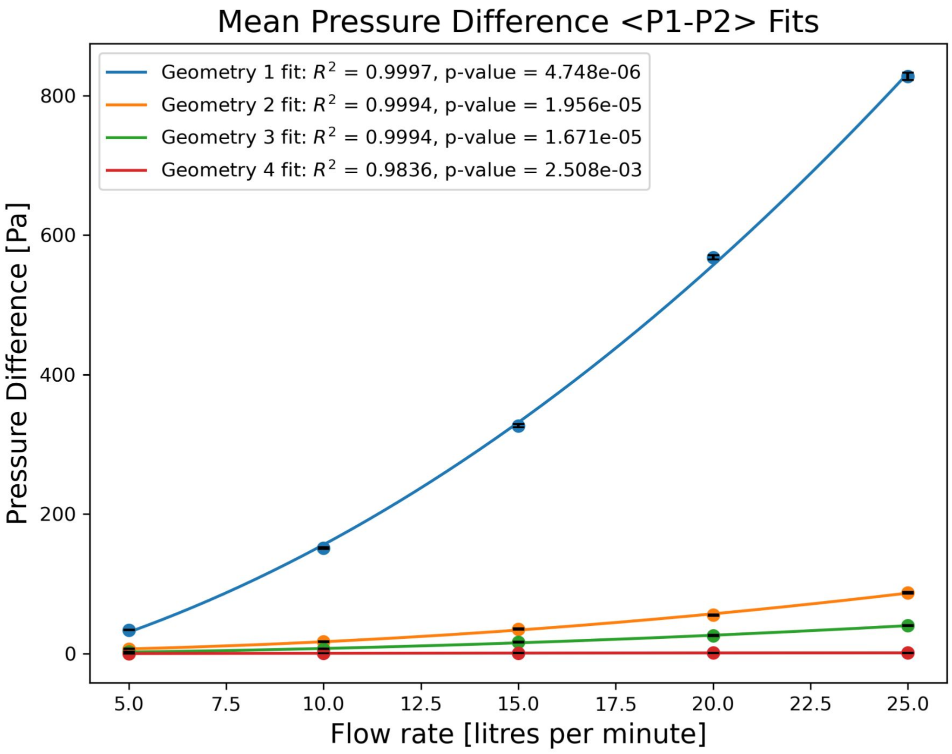


Dashed lines represent the theoretical values from Bernoulli's Equation.

Mean Pressure Difference for Geometries

Fit to a quadratic equation (analogous to Bernoulli's Eqn) $Ax^2 + Bx + C$

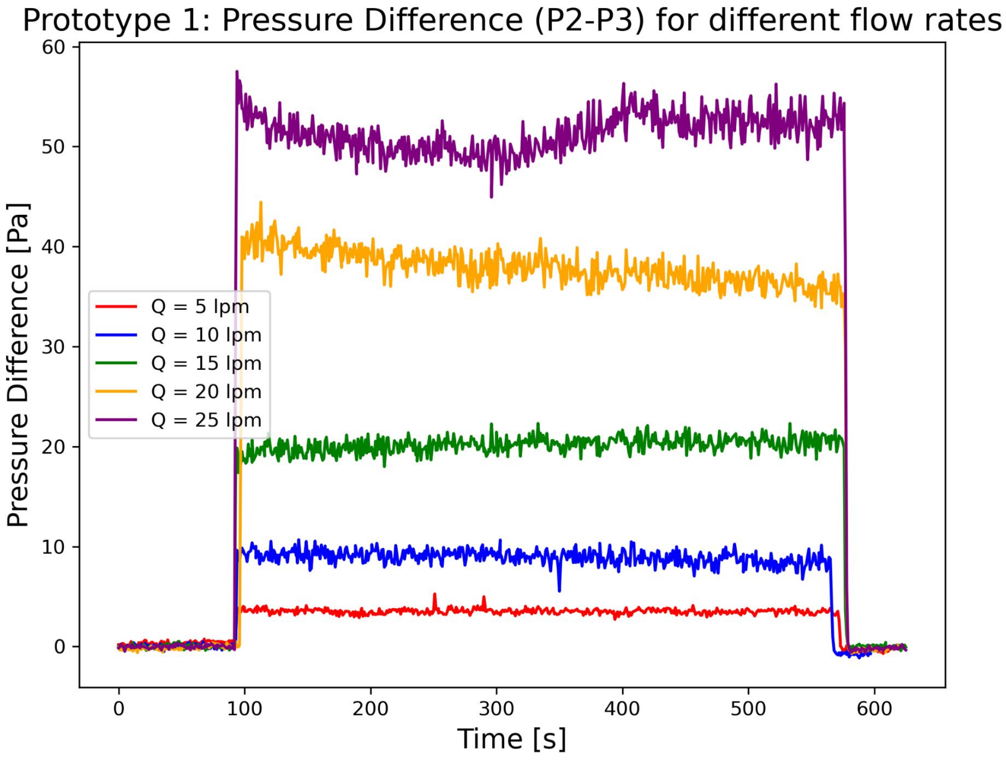
Error bars (1σ) very small (~1-6 Pa)



Pressure Difference between Middle Sensor and Outlet

Expect P2 - P3 < 0 from Bernoulli's Equation

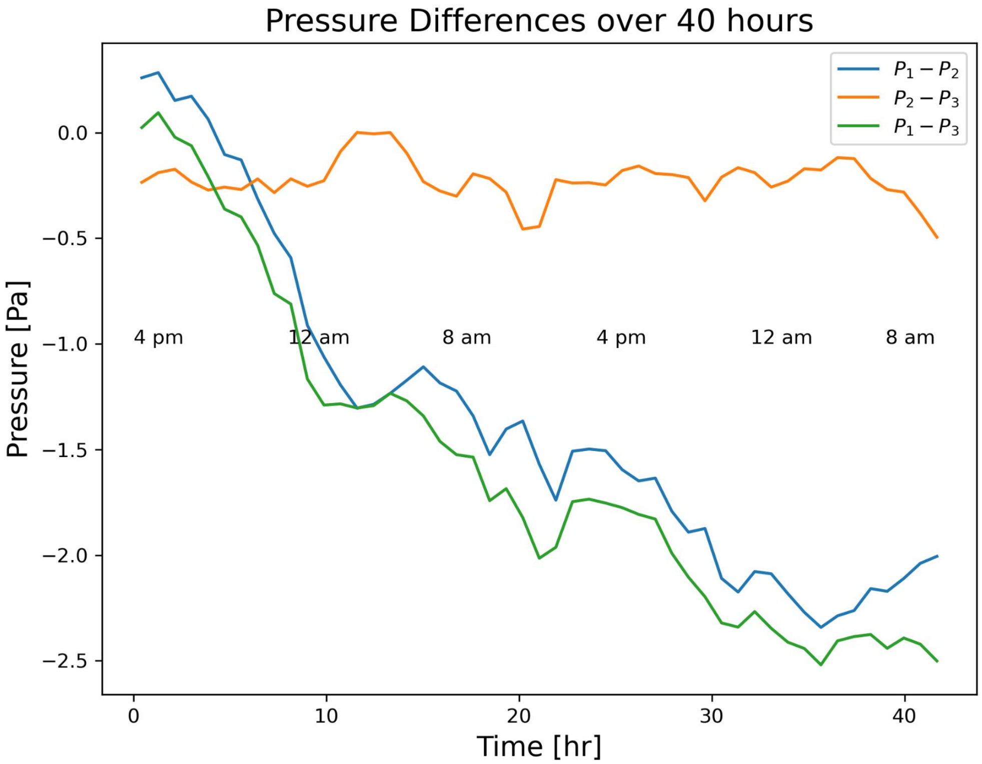
Turbulence? Energy dissipation?



Pressure Sensor Stability Over Time

Drift < 3 Pa over 40 hours

Much less than pressure sensitivity with airflow (10s - 100s of Pa)

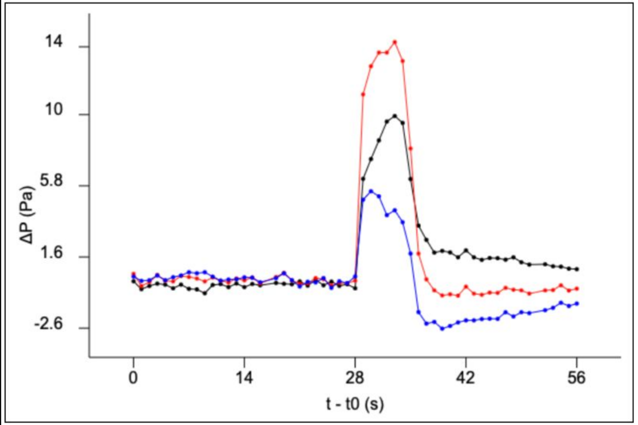


Offsets after turning air flow off

Small drifts (~<1 Pa) after turning air pump off

Montoring Pressures in the Ventilator Flowmeter

○ Simulated data ◉ Real data



t0: Tue Apr 09 2024 16:35:38 GMT-0500 (Central Daylight Time)
Black: P1 - P2, Red: P1 - P3, Blue: P2 - P3

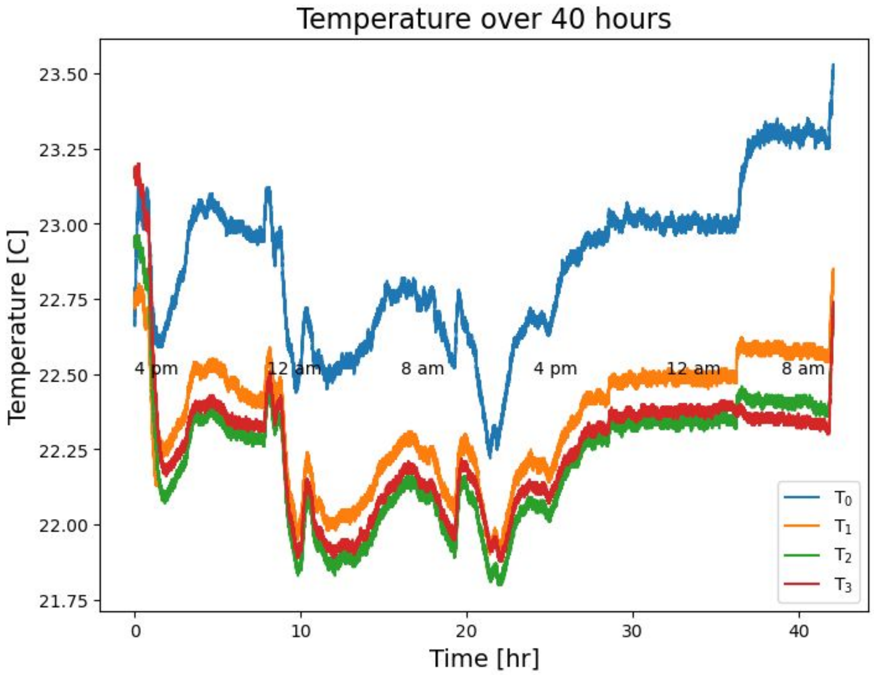
Number of points: 55

Latest time: Tue Apr 09 2024 16:36:34 GMT-0500 (Central Daylight Time)

Pressures recorded by the 4 sensors (Pa):
98660.76
98659.61
98658.73

Temperature Dependance

- Temperature Sensitivity of DPS310: 0.5 Pa/K
- No discernable temperature dependance over range of operating temperature (18-25 ºC)



Future Goals

- Testing prototype with respiratory simulation systems
- Integration with Carle Illinois College of Medicine with fully supported front end interface
- Performance comparisons with existing commercial flowmeters
- Patent registration

Summary

- Designed and tested different prototypes for ventilator flow meters
- Prototype can measure precise pressure differences (and hence flow rates) and is relatively affordable
- Capability of transmitting real-time data remotely for easy access by medical personnel
- Prototype 1's geometry is most stable

Coefficient of variation (Std Dev/Mean) <= 0.02

Thanks to Professor George Gollin and Professor Yuk Tung Liu for their technical support.

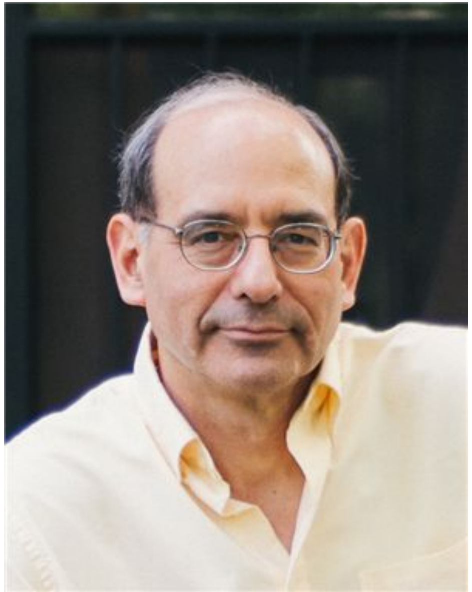
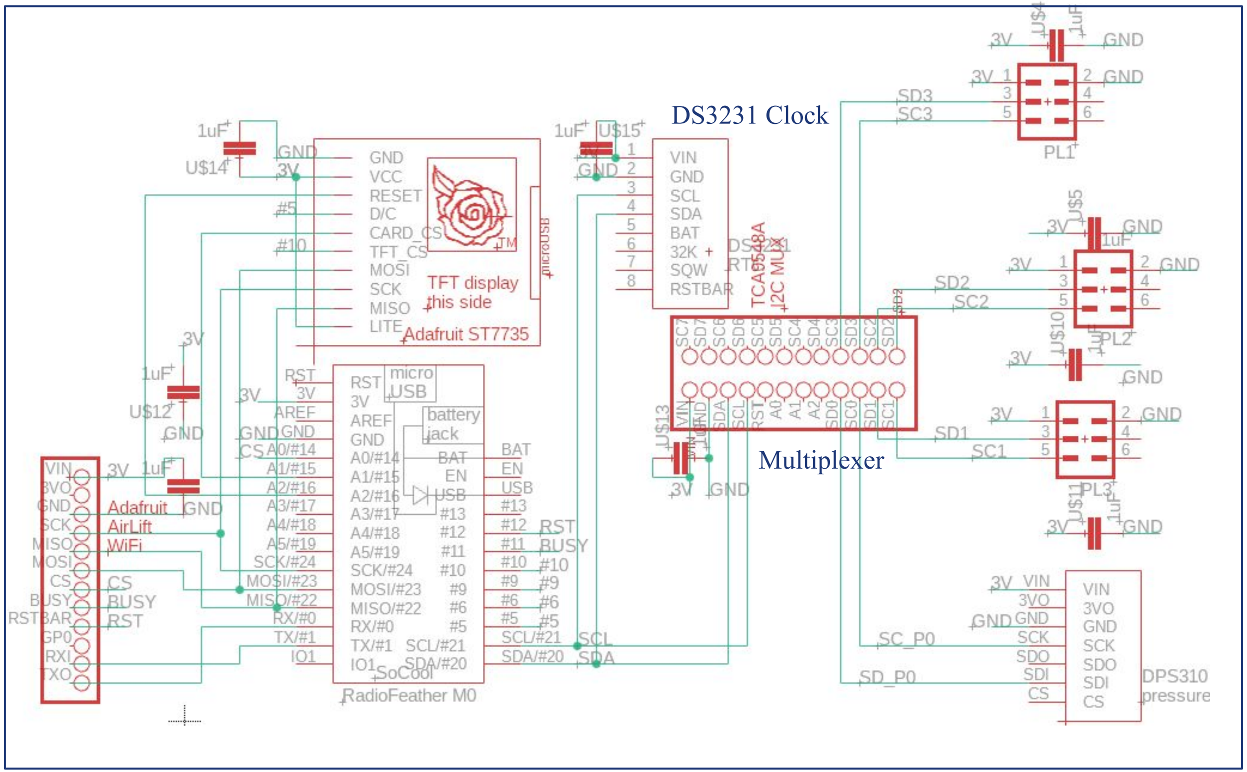


Photo credit: left: https://physics.illinois.edu/people/directory/profile/g-gollin; right: Jay Zhang

BACKUP SLIDES

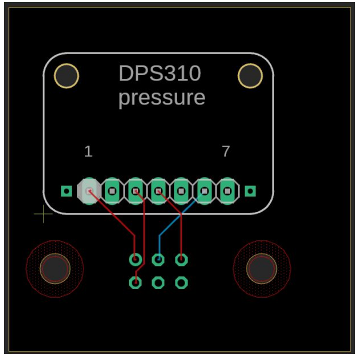
Schematics

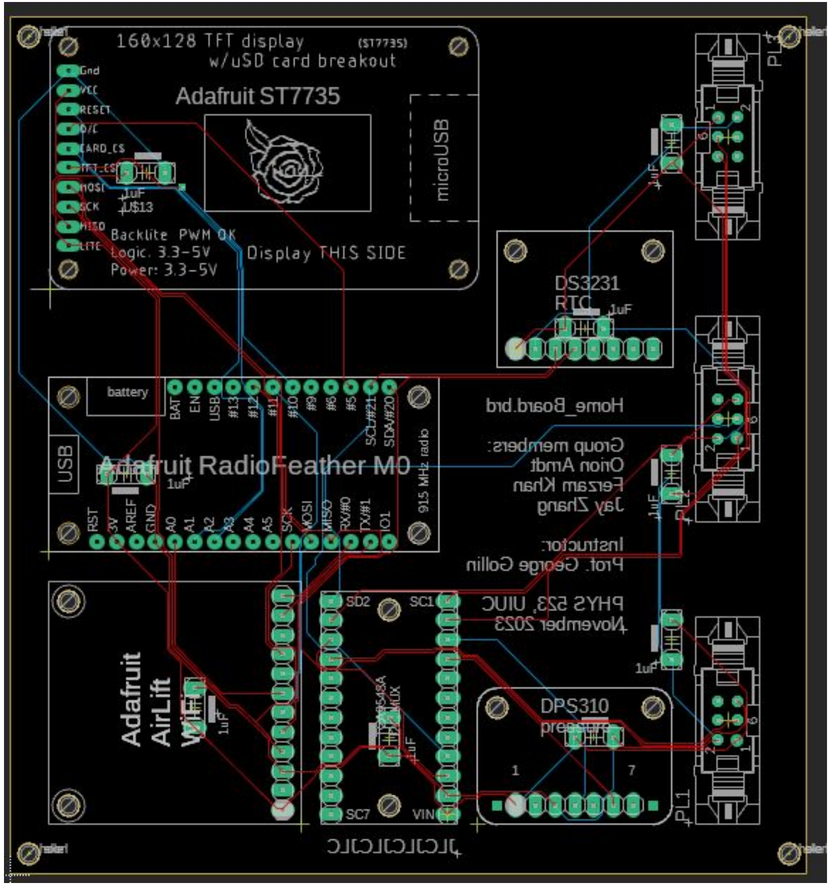


Home Board

Sensor Board

PCB Design


DPS310
pressure
1
7


160x128 TFT display
w/uSD card breakout
Adafruit ST7735
microUSB
Backlite PWM OK
Logic 3.3-5V
Power: 3.3-5V
Display THIS SIDE
DS3231
RTC
battery
USB
Adafruit RadioFeather M0
915 MHz radio
Adafruit
AirLift
WiFi
DPS310
pressure