Development and Performance of an IoT-Enabled Shirt Measuring Pulmonary Data

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0. Abstract

The majority of devices designed to measure pulmonary data, specifically lung volume, are invasive; attaching to the mouth and/or nose making them difficult to wear for long periods of time. This paper goes over our design, development, and performance of a noninvasive, IoT-enabled pulmonary data measurement device. Our device uses a system of capacitive sensors to measure the expansion of the chest which is simple in terms of its mechanical design but requires a detailed calibration process.

Code can be found at: https://github.com/GaneshPimpale/Pulmonary-IOT-shirt
Videos: https://tinyurl.com/me100VidDemo

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1. Motivation

The majority of devices designed to measure pulmonary data are invasive, usually mounting to the face coving the mouth and nose. In other situations, sensors are directly inserted into the lung cavity by creating a hold in a patient's chest.

A device containing passive sensors solves two main problems. First, medical needs, multiple diseases that affect the lungs can be detected by the symptom of rapidly decreasing lung volumes. Examples of such are pneumothorax, asthma, and others alike. Currently, patients with such diseases have to periodically use multiple devices to measure a set of volumes that indicate the condition of their lungs.

Taking a different approach, athletes would also appreciate this kind of data. Products like smart watches, power sensors, and chest straps allow athletes to track data about their bodies and correlate it to their physical performance. Training the respiratory system is important for all types of athletes and lung volume is valuable data to have on hand.

Over the course of the paper, we will be primarily evaluating our work from an athletic product perspective.

2. Background Research

2.1. Existing work

Products that measure lung volume passively do exist. An example of one is the Hexoskin smart shirt. However, these products are designed for sleep tracking, making them heavy, bulky, and not well suited for athletic performance.

2.2. Introduction to Lung Volumes

When discussing pulmonary data, we need to differentiate the various types of measurements that can be taken. This section provides a brief overview of lung volume and capacities.

Lung volumes refer to the different volumes of air present in the respiratory system during the respiratory cycle. Lung capacities are combinations of one or more lung volumes.

The lung volumes are

- Tidal Volume (TV): the amount of air that can be inhaled or exhaled during one respiratory cycle. This volume will increase by ~X5 factor during exercise
- Inspiratory Reserve Volume (IRV): the amount of air that can be inhaled after a normal TV
- Expiratory Reserve Volume (ERV): the amount of air that can be exhaled after a normal TV
- Residual Volume (RV): The volume that remains after maximal exhalation

Lung capacities are:

- Inspiratory Capacity (IC): maximum volume of air that can be inhaled, where **IC = IRV + TV**
- Total Lung Capacity (TLC): maximum volume of air the lungs can accommodate, where **TLC = TV + ERV + IRV + RV**
- Vital Capacity (VC): the total amount of air exhaled after maximal inhalation, where **VC = TV + ERV + IRC**
- Function Residual Capacity (FRC): The amount of air remaining in the lungs after each exhalation. As an approximation, **FRC = 0.8*(TLC)**

When discussing lung diseases, we can divide them into two types: obstructive and restrictive. In the case of obstructive diseases, the airway to the lung has some kind of obstruction causing resistance during the breathing cycle. Restrictive lung diseases occur when the lung stiffens and becomes less compliant and it shrinks.

Our device collects data (perimeter of the chest) that can be correlated with a specific lung volume. We will calibrate our device to measure the ERV and IRV making it a better indicator of obstructive lung diseases.

3. Design

3.1. Sensors

3.1.1. Sensor Design

In order to detect changes in lung volume, we are measuring changes in the size of the chest. Specifically, we are looking for a change in the length of the perimeter of the chest in a single dimension. To do this, we are making use of the ESP32's capacitive sensing pins. The design of the sensor is like so:

Figure 1: Diagram of the sensor design

The sensor consists of two main layers: a conductive fabric and a non-conductive gel layer underneath. These two layers are attached to a layer of fabric that sits above the skin. As the chest expands and contracts, the distance between skin and conductive fabric will increase and decrease accordingly.

The conductive fabric layer is wired to the capacitive sensing pin on the ESP32, allowing us to record the capacitance between the conductive fabric and the skin over time. When using capacitive sensing on the ESP32, the device will return a value relative to the variation in capacitance. That is,

$$C_{esp} = C_i - C_a$$

Where C_{esp} is the value returned from the ESP32, C_a is the actual capacitance, and C_i is a constant of the maximum possible variation in capacitance, we will be using the value 1000. Using this, we can derive:

$$d = \frac{c}{1000 - C_{esp}}$$

Where c is a constant and d is the distance between the skin and conductive fabric. We make a gross simplification and treat the chest as a circle. Its change in the perimeter is approximately the same as a circle's change in circumference and d is the change in the circle's radius such that:

$$p \approx Circ = \frac{\pi(r+d)}{2}$$

Allowing us to approximate the change in chest size as a user breathes. Code to use the ESP32 capacitive sensing pins can be found here:
https://github.com/GaneshPimpale/Pulmonary-IOT-shirt/blob/main/cap_read.py

3.1.2. Manufacturing the Sensors

The sensor itself consisted of two main components: the conductive fabric, and a silicone dielectric. The conductive material was bought online, came in a small 5”x5” piece, and was a two-way stretch. One side was significantly more conductive than the other. To make the dielectric, silicone molding material, Ecoflex 10, was poured into a mold of a flat sheet. Ecoflex 10 was chosen over other materials due to its stretchability, and it was the softest silicone in stock.

The conductive fabric and silicone sheet were then cut into rectangles of approximately the same size - the conductive fabric was cut to a slightly smaller width to ensure that there would be no contact between them. Then, the sensor was assembled by placing the two pieces of conductive material on either side of the silicone piece. They were attached to each other using a zig-zag stitch in order to ensure that the sensor would be able to stretch even after it was sewn together, due to the fact that the thread had no stretch. It was important to ensure that the thread was non-conductive as well.

Due to the high friction of the silicone, it was very difficult to sew to the conductive fabric with the sewing machine, as the stepper foot would catch and stretch out the silicone as it sewed. Therefore, a sheet of thin tissue was placed between the stepper foot and the silicone to reduce friction. After sewing, this was easily torn off. Below, the sensor can be seen in Figure 2.

Figure 2: Capacitance sensor integrated into the shirt

3.1.3. Sensor Calibration

One of the side effects of measuring capacitance is how easily the measurement can be affected by external factors. To address this, there is a detailed calibration process.

First, the user must exhale until they have reached the vital capacity, the maximum amount of air that can be exhaled. At this point, the chest has reached its minimum perimeter. This process is done multiple times (5 times) and averaged to establish a baseline value. During this process, the user also has to use a spirometer to measure their expiratory reserve volume (ERV). The ERV is also averaged.

This process allows us to determine the capacitance value when the lungs are full and empty. The result of this calibration process will be demonstrated in section 4.

3.2. Actuation

As a wearable device, it can be difficult to look down for visual indicators (i.e. LEDs or displays) so we opted to provide the user with haptic feedback. This was done by attaching a motor to the shirt on the right pectoral. This is a part of the chest that does not move drastically and results in a consistent feeling when turned on.

Our system provides feedback during acceleration. We made use of the LM6DSO IMU to track the acceleration in the X, Y, and Z directions. The frequency at which the motor vibrates would be a function of the magnitude of acceleration.

Code for the motor control loop and IMU can be found here:
https://github.com/GaneshPimpale/Pulmonary-IOT-shirt/blob/main/motor_control.py

3.3. Communication

In order to communicate with our device, we used the MQTT system. Although this made a simple implementation, we were limited by the low data rate. A preferable alternative would be Bluetooth (BLE). BLE provides two advantages: First, direct communication with a mobile device which removes the need for a wireless network to be available. Second, it allows for a much higher data rate allowing real-time communication between a mobile device and the shirt.

4. Performance

This section will go over the full process of using the device and analyzing the data. Videos of our demonstration of the device can be found here:
https://tinyurl.com/me100VidDemo

Before the device can be worn the user must first warm up. First, during the warm-up process, the tidal volume of the lungs will drastically increase resulting in larger chest expansions and smaller chest compressions. Second, the user will heat up and change the body's dielectric properties as the blood flow underneath the skin increases and the body temperature increases. We used heart rate as our indicator for the warm-up period. Once a heart rate of over 140 was held for 5 minutes, the warm-up process would be completed.

At this point, the calibration process (section 3.1.3) will be run and the device is ready to use. Below is the raw data we received during the trial:

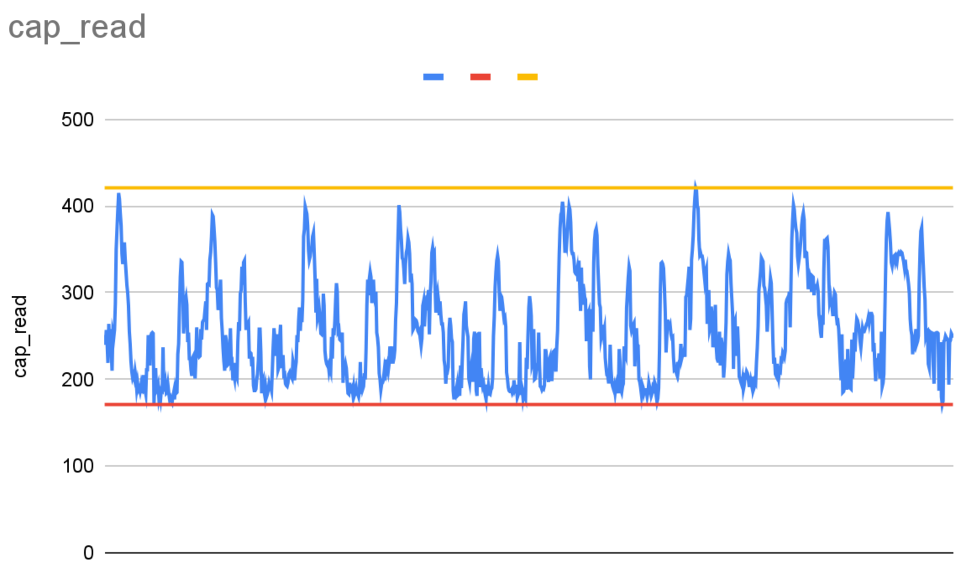

Figure 3: cap_read value over time. max(orange): 421, min(red): 171

The orange and red lines indicate the minimum and maximum chest size as measured from the calibration process. If environmental changes were affecting the capacitance sensing after the calibration process, we would be presented with a graph like figure 4 below:

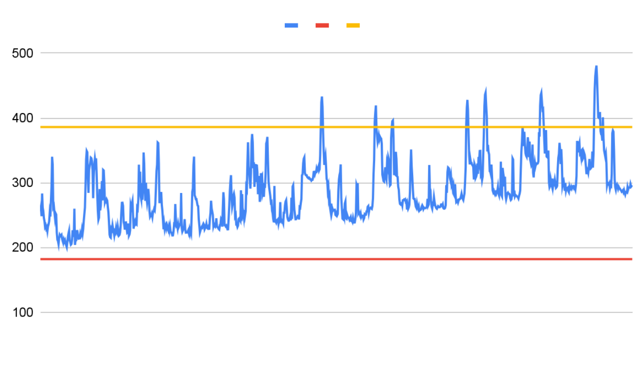

Figure 4: An example of corrupted data

Once we are presented with correct data, we can transform it into a graph of d and p:

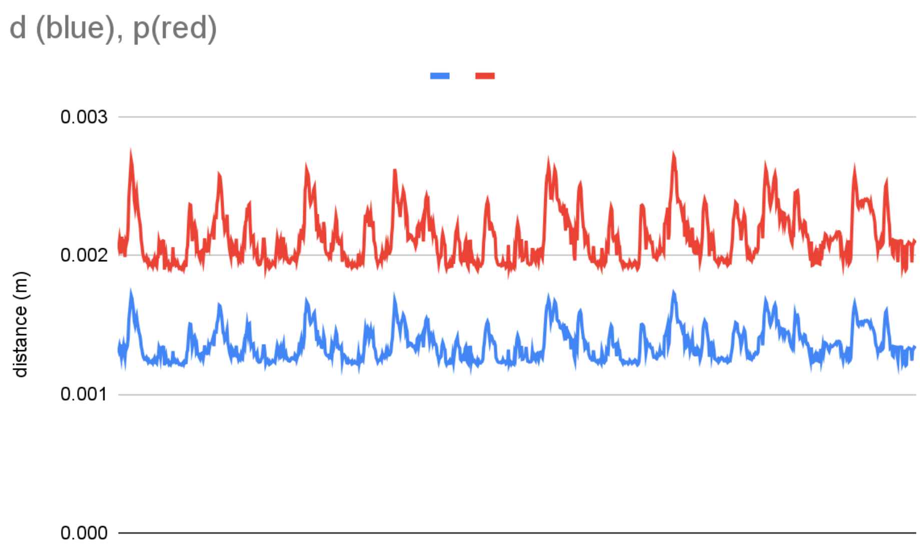

Figure 5: graph of change in d and p values

Finally, we can use the ERV determined in the calibration process in the equation:

$$V = d\frac{ERV}{min(d)}$$

To linearly correlate the measured ERV to the data. This produces the following:

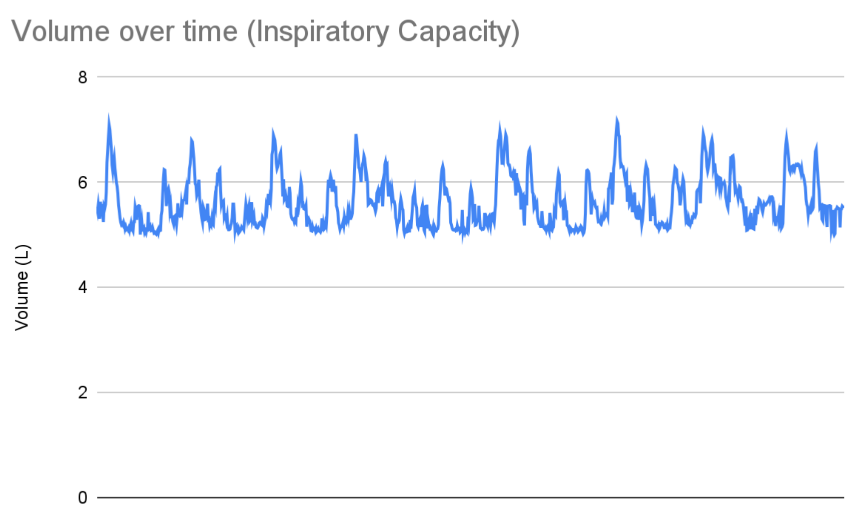

Figure 6: Graph of lung inspiratory capacity over time.

Which is the inspiratory capacity of the lung. To calculate the ERV, we can subtract the lung's tidal volume and produce:

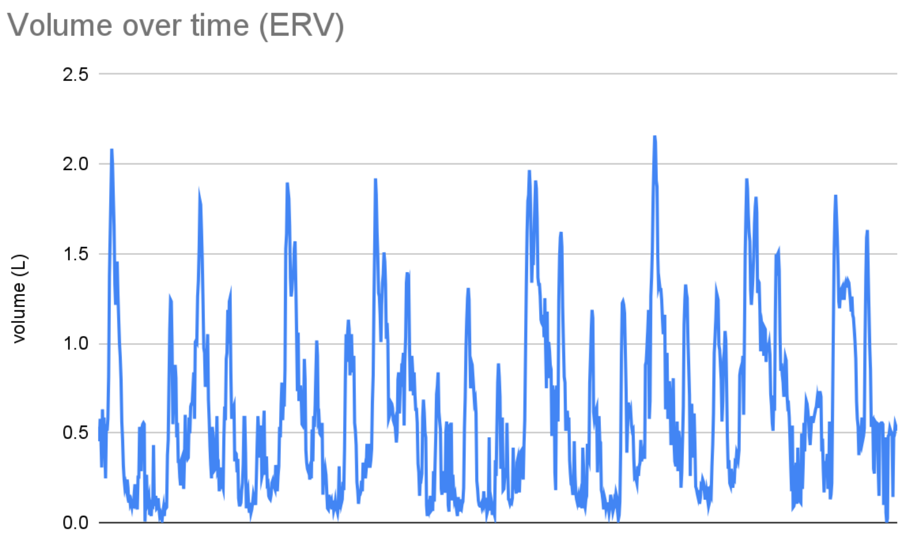

Figure 6: Expiratory reserve volume over time

Which is the ERV over time, the value we are calculating for.

5. Review

5.1. Future Work

When using the device there were quite a few issues with the fit. These could be easily fixed by better integrating the strap with the shirt. If the device was to be made as simple as possible, it would require shoulder straps in order to keep it from falling during use. Additionally, Bluetooth would be a far more preferable option over MQTT since it allows for a higher data rate and does not require a network.

In terms of more broad goals, we would want to compare this capacitive system to one that uses a fabric with a variable resistance as a way to measure the change in chest size. A system that uses resistance may result in a more sleek and low-profile final product.

5.2 Conclusion

Pulmonary data has many uses from medicine to athletics and there is a need for a low-profile, noninvasive system. Over the course of this project, we developed a system to estimate the lung's expiratory reserve volume by measuring the capacitance between the body and the device. This system is easy to implement, but it requires a specific calibration process and is easily susceptible to environmental fluctuations (other layers of clothing, weather, etc.).

The prototype we created demonstrated a potential future for this type of sensor and feedback system to be integrated into mainstream devices.

Bibliography

Ranu, H., Wilde, M., & Madden, B. (2011). Pulmonary function tests. *The Ulster medical journal*, *80*(2), 84–90.

Vollrath , M., & Guevara , M. (n.d.). The McGill Physiology Virtual Lab: Lung Diseases. Lung Diseases. Retrieved from http://www.medicine.mcgill.ca/physio/vlab/Other_exps/resp/Lungdiseases_n.htm

Wanger, J., Clausen, J. L., Coates, A., Pedersen, O. F., Brusasco, V., Burgos, F., Casaburi, R., Crapo, R., Enright, P., van der Grinten, C. P., Gustafsson, P., Hankinson, J., Jensen, R., Johnson, D., MacIntyre, N., McKay, R., Miller, M. R., Navajas, D., Pellegrino, R., & Viegi, G. (2005). Standardization of the measurement of lung volumes. European Respiratory Journal, 26(3), 511–522. https://doi.org/10.1183/09031936.05.00035005