Ventilation Monitor
Midsemester Report

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Advisor/Client: Prof. John G. Webster

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Background Information

As the ventilation team, our goal is to design a device which will measure the respiration rate of the firefighter wearing it. Our device will send a wireless signal to a command center. At this command center, personnel will be able to monitor the breathing rate of the firefighter wearing our device.

The need for this device is to increase firefighter safety. In an emergency situation, firefighters are exposed to many dangers such as smoke. Although most firefighters wear numerous protective devices to prevent the inhalation of these toxins, 123 deaths have occurred due to asphyxiation in the last ten years (U.S. Fire Administration, 2007).

Year	Deaths
2006	12
2005	8
2004	5
2003	6
2002	15
2001	18
2000	13
1999	16
1998	15
1997	15

Table 1: U.S. firefighter deaths by asphyxiation per year (U.S. Fire Administration, 2007).

The overall goal of the ventilation monitor is to alert rescue personnel if a firefighter’s breathing rate reaches dangerous levels. If this were the case, the firefighter could be rescued and given medical attention before the situation becomes fatal.

Some devices measuring ventilation exist today. These devices use a variety of designs and technologies. The most popular technology used is inductance plethysmography. This technique is noninvasive and is used to measure a change in lung volume. Most inductive plethysomgraphers are built using a chest strap. This strap is embedded with a circuit fashioned in a way that stretching of the strap changes the inductance. The strap around the chest acts as a circuit loop. As the person wearing this strap breathes in and out the chest expands and contracts. This expanding and contracting of the chest changes the cross-sectional area of the loop. Magnetic flux is a function of the area of a loop according to the equation:

$$\Phi_m = \iint \mathbf{B} \cdot d\mathbf{S}$$

Magnetic flux (Φ), magnetic field (B), and surface area (S) (Serway and Jewett, 2004)

$$L = \frac{\Phi}{i}.$$

Inductance (L), magnetic flux (Φ), and current (*i*) (Serway and Jewett, 2004)

Breathing changes this surface area by expanding a chest strap and thus changes the flux, which changes the inductance of the circuit. Through the use of different circuit elements, inductance plethysmography turns this inductance into a voltage. This voltage can be wirelessly transmitted.

Design Specifications

According to criteria established in meeting with our client and through literature research, our device must fulfill several requirements. The device must be able to detect expansion and contraction of the chest and wirelessly transmit that data to a nearby command post. The inductance band itself must be able to fit most firefighters comfortably meaning that it must not slip as the firefighter wears it, nor cause itching, irritation, or rashes. It must also be less than one pound so as not to interfere with the firefighter's range of motion. Since the device will be worn next to the skin, it must be able to accommodate temperatures near 110 °F and withstand moderate amounts of moisture due to sweat.

The device will be used frequently, so the fabric and wire must be resistant to wear and cannot rip. The belt itself must be easily cleaned/sterilized. Ideally it will be washable. We expect the device, with proper maintenance and periodic replacement of the power source, to have a life in service of at least five years.

Current Products

There are currently several devices that are designed to monitor firefighter ventilation on the market today, but they are quite expensive. Our aim is to create a simplified device that does not have all the extra functions of current products, but as a result is much cheaper.

Figure 1: The monitoring belt for the VivoMetrics® VivoResponder™ (VivoMetrics, Inc. 2007)

One well-established device is the VivoMetrics® VivoResponder™ system (Figure 1). It is similar to our proposed device in that it measures respiration using an inductance plethysmography chest band. The band is lightweight (4 oz.) and comfortable. Data is wirelessly transmitted to a command center, as we plan to do. The cost of the device – $2500 to $8000 for a single unit – is much more than our target price.

The VivoMetrics® VivoResponder™ is so expensive because it offers many features. In addition to rate of respiration (what we plan to measure), it also monitors heart rate, skin temperature, activity, and posture (VivoMetics, Inc., 2007). It is easy enough to measure skin temperature and heart rate, but posture and activity would be slightly more complicated. We think that measuring these variables is what increases the price of the VivoMetrics® VivoResponder™ so drastically because it would require more advanced sensors, such as accelerometers. We believe that by limiting ourselves to monitoring breathing rate, we will be able to provide a device at a fraction of the price.

A second device currently available today is the MSA TxR ICM® Accountability System (Figure 2). Rather than a strap-based system, this device is meant to be integrated with a self-contained breathing apparatus (SCBA). It monitors temperature and has an accelerometer to monitor how/if the firefighter is moving. It also monitors breathing rate and the amount of air left in the SCBA system. From this data, it is able to calculate how much longer a given SCBA tank will last. The device also has a two-way communication system that allows the command center to issue an “evacuate” command. The firefighter can confirm reception as well as initiate a distress signal.

Figure 2 - The MSA TxR ICM® Accountability System. The unit with the computer is the sensor and also serves as a miniature display. (MSA, Inc,. 2006)

This device is slightly cheaper than the VivoMetrics® VivoResponder™. It starts at $1800 per unit. We believe that this device is so expensive in part because of the inclusion of a solid-state accelerometer (MSA, Inc., 2006). Again, we hope to keep our device affordable by eliminating the use of such expensive sensors.

Inductance plethysmography straps are also available commercially. Again, they are too expensive for our purposes so we will design and build our own strap. The first strap we looked at was the MVAP Respiratory Inductive Plethysmography (RIP) belt (Figure 3). According to the company catalog, the belts start at $260.

Figure 3: MVAP RIP belt
(MVAP Medical Supplies, Inc. 2006)

Another company that sells inductance plethysmography belts is Ambulatory Monitoring Inc. A band for a regular adult (28” to 36” chest circumference) costs $70 (Ambulatory Monitoring, Inc., 2005).

Chest Strap Design

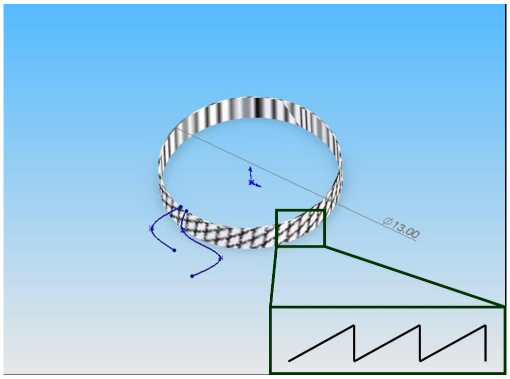

Figure 4: Chest strap design. Wire will be woven through the knit cotton fabric in a zigzag pattern as shown in inset. Two leads will connect the strap to the rest of the circuit.

Our chest strap will be based on an old belt used by the UW Sleep Apnea Lab. It will be made of cotton knit fabric which costs $2.50 per square yard. Cotton knit will work well because it is lightweight, flexible, and breathable. The belt will be fastened by Velcro, and two wire leads will connect the belt to the rest of the circuit. The belt will be designed to fit chests from 30” to 50” in circumference. Wire will be woven through the fabric in a zigzag pattern (Figure 4). This belt will be used in designs one and two, and a modified version will be used in design three. The modified version does not include a wire running around the chest strap but will instead package all components on one side of the belt.

Design 1: Inductance plethysmographer featuring Colpitt’s Oscillator

Our first design uses an oscillator and an isolation circuit in order to deliver an output voltage that will be transmitted to a command center.

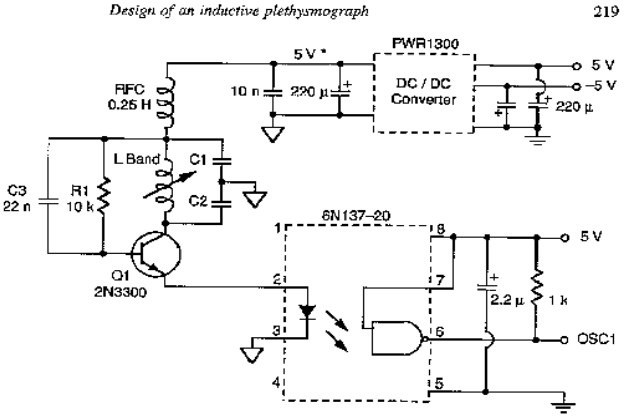

Figure 5: A diagram of an oscillator and isolation circuit. L_{band} represents the inductance of the firefighter’s chest strap. (Cohen et al*, 2004)*

The frequency of the oscillator can be represented by the equation:

$f_0 = [LC_1C2/(C_1 + C_2)]^{-1/2} / 2$ (Cohen *et al*, 2004)

Frequency of the oscillator at the bipolar junction transistor is thus proportional to $L^{-1/2}$, but for small changes in chest strap inductance, we can treat the frequency change as linear and approximate it by a Taylor polynomial (Cohen *et al,* 2004). The amplitude of oscillations drive an emitter and an isolated circuit will then generate an output voltage that can be sent to a command center. Cohen *et al* describe a number of assumptions about connectors to the circuit. Coaxial cables and other wires should not have inductance, and if there is any it is assumed to be substantially smaller than that of the inductor.

This design is good because all of its components are relatively cheap and it only requires a 5 V power source. It is also very portable because all circuit elements are small. The output signal is accurate because of a phase-locked loop (PLL) that is also part of the design. The PLL locks onto the frequency and thus eliminates baseline and phase discrepancies of the oscillator. Amplification of the signal is very accurate, and a consistent, measurable output voltage proportional to area of the chest strap can be obtained. The only disadvantage to this circuit is its complexity. This design team is made up entirely of sophomores, and we need to fully understand the principles of this circuit in order to build and test a prototype.

Design 2: Inductance Plethysmographer featuring a Low-Pass Filter

Our second design also uses the principle of inductance plethysmography to monitor breathing rate non-invasively. Again, a wire is sewed into a chest strap, and when a current runs through this wire there is self-inductance in the band. In this design, the inductance band is an element in a low-pass filter:

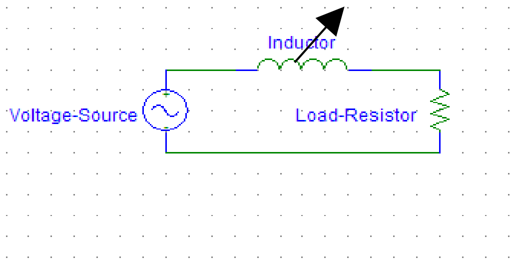

Figure 6: *A low-pass filter with the chest strap band as the inductor. Inductance is variable and is based on the chest strap. The voltage source and resistor values are not specified because we do not yet know what sort of values to expect for the inductor. These values will be determined after testing.*

The corner frequency of this circuit is variable as R/(2 L), but the frequency of the voltage source is always constant.

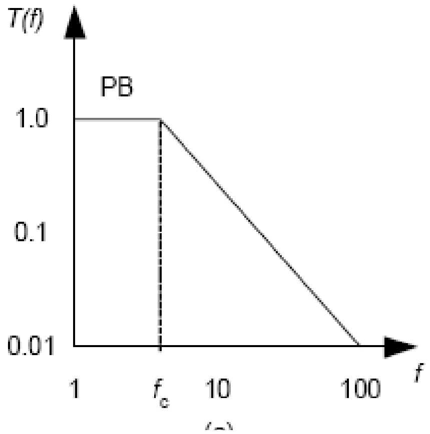

Figure 7: *The frequency response of a low-pass filter. When frequency goes above the corner frequency* f_c*, the voltage input is attenuated and the output is very low. (Webster, 2004)*

As the inductance of the chest strap varies, the corner frequency is proportional to L^{-1}. As inductance increases with cross sectional area of the chest strap, the corner frequency will shift left. The voltage source frequency should be set to the maximum corner frequency – when the chest strap is completely contracted. When the corner frequency shifts left, the voltage of the source will be attenuated and there will be a lower output voltage. The output voltage would be amplified and transmitted to give a ventilation reading.

The value for the resistor was not chosen because the chest strap inductance needs to be determined. The inductance needs to be determined by testing because there will only be one loop around the chest and the resulting inductance change will be very small. The voltage source will be relatively small (less than 5V), and its value was not chosen yet because we do not know how much the corner frequency will vary. If there is too small of a change in corner frequency, then the attenuation of the filter will not be large. If a differential amplifier is used, the input difference (V_{source} - V_R) will be too small to yield a large enough output voltage. If we cannot get a large enough frequency shift, then the voltage source would need to have a higher voltage in order to provide a large enough input difference for the amplifier.

This design is desirable because of its simplicity, but there are a few problems that render it ineffective. First, there can be baseline shifts, and because we are operating based on a very small change of inductance, the baseline could very easily go off the scale and saturate our output device. Also because of the small change in inductance, using a comparator or differential amplifier would be difficult. The change

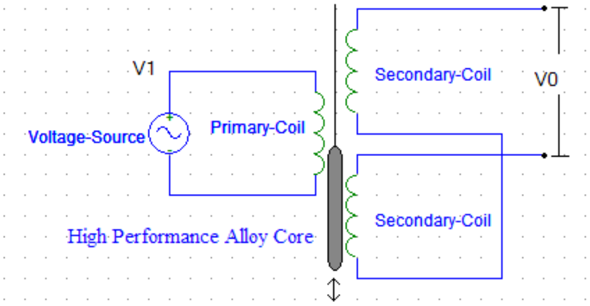

Figure 8: *A diagram of an linear variable differential transformer.*

in voltage may be too small to measure. However, a trim potentiometer might mitigate this problem. Second, as the corner frequency approaches the frequency of the source, the phase of the inductor falls from 90 degrees to 45 degrees. As a result, we may not be able to amplify our output voltages.

Design 3: Linear Variable Differential Transformer (LVDT)

Our third design is a linear variable differential transformer (LVDT). It is unlike the other two designs because it does not use inductance plethysmography. As the chest of the firefighter expands and contracts while breathing, a ferrous rod slides inside of a tube through three sets of coils. An alternating current is driven through the primary coil as seen on the left in Figure 8. This causes a voltage to be induced in each of the secondary coils proportional to that of the primary. As the core moves through the system, these mutual inductances change, causing the voltage induced in the secondaries to change. This change in voltage can be transmitted to the command center.

This design has two positive aspects. First, it has proven to be extremely accurate and easy to measure because the change in voltage in voltage is large. The circuitry is not complex and the output of the sensor is a voltage, so the conversion of an inuductance to a voltage is not required. Unfortunately, it is quite expensive. According to manufacturers' websites the LVDT unit can cost between $115 and $800 (Omega, 2007).

Design Matrix

The LVDT scored so poorly on the design matirx (Table 2) in the cost category precisely because of its high cost. The other two designs are composed of cheap circuit components, which is why they scored higher. Cost was an important consideration for us because our goal is not to create new technology but compete against existing ones.

	Weight	**Colpitts Oscillator**	**Low-pass Filter**	**LVDT**
Safety	20	**18**	18	15
Signal Strength	25	**17**	10	22
Comfort	15	**13**	13	8
Cost	20	**15**	19	4
Manufacturability/feasibility	20	**16**	12	18
Total	100	**79**	72	67

Table 2: Design Matrix. Based on this evaluation, we chose the Colpitts Oscillator as our final design with a total score of 79 out of 100 points.

Our highest weighted category was signal strength. The LVDT design scored the highest in this category because unlike the other two designs which use inductance plethysmography and give very small voltage differences, an LVDT gives a large voltage output. Thus, the voltage is easily amplified before it is transmitted to the command center.

Safety is an important category simply because this device is to be worn by people whose main priority is safety. The firefighters who ultimately wear the final product should not have to be worried about the safety of their equipment in high-stress situations. LVDT scored lowest in this category because it requires a higher voltage.

Manufacturability/feasibility was the last category of large importance. We want this device to be scaled to mass production and readily available circuitry is not difficult to manufacture. The LVDT is readily available and easily manufacturable. The low-pass filter scored low because, as to date, there have been no advancements in solving the problem of base-line shifts. Thus, the low-pass filter may be manufacturable but is not feasible. Ultimately, Design 1, the Colpitt's Oscillator was chosen to be the final design based on the design matrix.

Future Work

After having chosen the Colpitt's Oscillator as the final design, we now have more work to do by the end of the semester. We have to purchase or build the oscillator and other circuit components, arrange those components into a working prototype and then test that prototype. This prototype will consist of the chest strap with wire sewn into it.

We also need to do some further research on methods on how to transmit the voltage wirelessly. Our first goal is to be able to read a voltage from the prototype of the belt. Once this is achieved, wireless transmission technology will become the focus of study.

Potential Problems

The main problem that could result from any of our designs is that chest expansion does not result in a large enough change in inductance to give a signal. The oscillator circuit was originally designed to account for this problem, but if necessary we will have to redesign the strap so that the wire loops around it more times. The only other problems we anticipate are those associated with understanding and building the circuit.

We plan to keep close contact with Professor Webster so that he can help us with any problems we have with understanding the circuit. On another note, the group may take a lot of time to build the chest strap and sew the wire in because none of us are very good with the needle. This part of the project should ideally only take an hour or two, but we need to anticipate it taking longer and plan accordingly.

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Appendix 1: Product Design Specification

Ventilation Monitor

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Client: John Webster, PhD
Advisor: John Webster, PhD
Last Updated: 3/9/08

Function

We intend to develop a wearable, expandable chest strap to measure and transmit ventilation data to a central command center. This device will be especially useful to monitor the vital signs of firefighters and other first responders in hazardous situations. We hope to deliver a more inexpensive product than current models on the market.

Client Requirements

Fits under clothing
Measures respiration
Real time remote data
Light, durable material
Comfortable
Transmits data

Design Requirements

1. **Physical and Operational Characteristics**
    a. Performance requirements – withstand daily use, easy to put on

    b. Safety – No exposed wires, no risk of shock/short circuit, no interference with other devices.

    c. Accuracy and Reliability - Should send a signal indicating whether the firefighter is breathing or not.

    d. Life in Service – 5 years

    e. Shelf Life – 5 years

    f. Operating Environment – Must tolerate moisture, temperatures up to 110 degrees Fahrenheit, repeated stretching.

    g. Ergonomics – No slip, minimal rotation, male vs. female form

    h. Size – Variable girth, less than ¼ inch thick, width 4-6 inches

i. Weight – not more than 1 lb

j. Materials – knit cotton fabric, Velcro, basic circuit elements.

k. Aesthetics, Appearance, and Finish – texture should be smooth so as not to irritate skin.

2. Production Characteristics

a. Quantity of units needed – 1 prototype, but a mass producible design

b. Target Product Cost – $100

3. Miscellaneous

a. Standards and Specifications – N/A

b. Customer – NONE

c. Patient Concerns – washable, non-allergenic

d. Competition – Vivometric VivoResponder (pat #468-6999), PASS (no signal, alarm), Fireeye Heads-up display, Sensetech interwoven fabric, MSA ICM TxR Accountability System