MONITORING LUNG DISEASE USING ELECTRONIC STETHOSCOPE ARRAYS

Kyle Mulligan, Andy Adler, and Rafik Goubran
Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario

INTRODUCTION

Respiratory support is a lifesaving therapy, but it also augments the risk of contracting complications attributable to the endotracheal tube, positive pressure ventilation, or sedation. It is essential to develop strategies to optimize respiratory support in order to minimize the development of these complications. Management of such patients is difficult because the underlying pathologies are dynamic and unstable. Recent evidence has shown that lung protective ventilation strategies lead to dramatic improvements in patient health by reducing ventilator induced lung injury (VILI)[1]. To protect against VILI, many novel modes of ventilation have been developed; however clinicians have difficulty choosing optimal ventilation parameters, because patients' lungs are highly heterogeneous and change rapidly. The instruments currently available either don't provide regional information (ie SpO2), or temporal information (ie X-ray CT)[2].

In this paper, a novel medical instrument designed to measure changes in the distribution of lung fluid and lung tissue density is described. The key design focus of this apparatus is for monitoring the lung parameters needed to manage respiratory support. This detailed information on the changes in the regional distribution of lung air volumes, and lung fluid accumulation should allow more careful management of patient ventilatory status, which would result in improved patient health and reductions in the duration of ventilatory support in ICU.

The prototype lung monitoring system consists of an array of four electronic stethoscopes embedded into a fully adjustable harness. The harness is designed to attach to chest phantom models and both males and females of varying physiques. Secondly, a speaker with a funnel attached is used to input a White Gaussian Noise (WGN) signal into a patient's lungs via the mouth and measured by the stethoscope array on the chest surface. The recovered sound signals are analyzed using a computer with an overall goal of providing physicians with spatial information of pulmonary obstructions, and an index rating the effectiveness of an administered lung treatment based on changes in lung tissue density.

METHODS

In this section, the mechanical instrumentation design, and the data acquisition and processing techniques are described.

A. Apparatus

The sound recording and emitting interfaces require 5 off the shelf (OTS) components: laptop computer, pre-amplifier, speaker, funnel, and stethoscope (x4). Figure 1 illustrates a block diagram of each of the top level OTS components including their internal components. The importance of the internal components is to help visualize the numerous steps in data acquisition and thus how hardware delays originate.

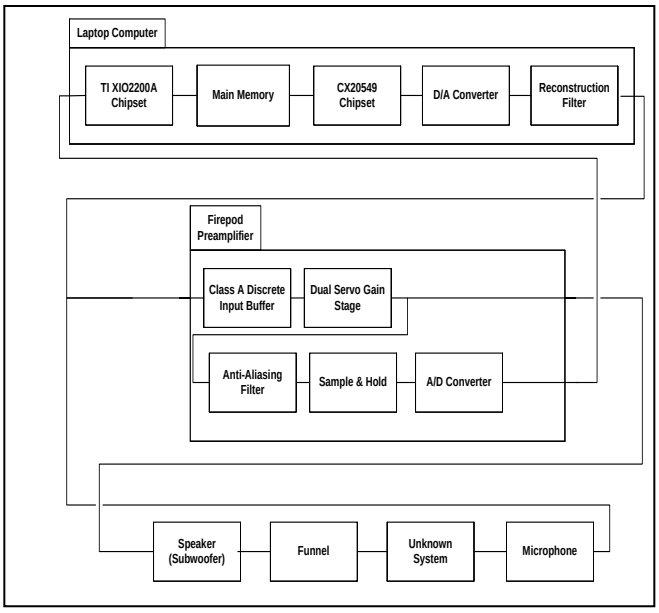

Figure 1: Block Diagram showing the various Off the Shelf (OTS) components including their Internal Components Used to Build the Sound Acquisition System. The Black Lines Represent an Audio Connector between the Components. Also Shown is the Location of the Unknown System (in this Case a Chest Phantom or Human).

B. Data Acquisition

Following the collection of components required to acquire the necessary data, before data acquisition could begin, there were preliminary steps to be followed including: the design of a structure that firmly attaches the stethoscope heads to the desired surface and location, the determination of an appropriate frequency span for the input signal in order to recover only relevant frequencies in the system transfer function, setting an appropriate pre-amplifier sampling frequency such that no information from the signals recovered from the stethoscopes was lost, and development of software to capture sound signals from the sound acquisition hardware that are calibrated to account for hardware delays

C. Data Processing

Following the acquisition of sound signals, processing the data involved: determining an appropriate algorithm for analysis of the input signal propagation characteristics, testing the algorithm against other well know methods that yield similar results, obtaining useful parameters from the algorithm and develop an index measuring the effectiveness of lung treatments

D. Adaptive Filtering

Adaptive filtering is widely used in order to identify the behavior of an unknown system. The basic principle involves passing an input signal into a desired system and measuring its output. At the same time, the input signal is passed through a Finite Impulse Response (FIR) filter composed of a set of delays and adjustable coefficients. The process is iterated until the output of the "adaptive" FIR filter matches the output of the unknown system. Generally, such filters assume that the behavior of the unknown system is linear and build its transfer function using the resulting set of delays and coefficients, along with other primitive operations (adders and multipliers). Depending on the values of the coefficients, an FIR filter can yield a frequency response of a variety of filters such as a: low pass, high pass, or a band pass filter.

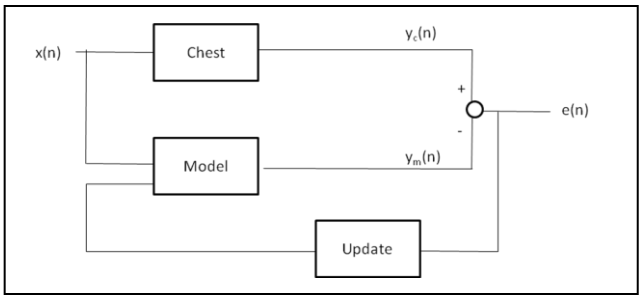

Figure 2: NLMS Adaptive Filtering Algorithm Block Diagram

A block diagram of the adaptive filtering structure employed is shown in Figure 2. The coefficient algorithm that is employed is the Normalized Least Mean Squared (NLMS) algorithm. The coefficient values are updated at each iteration using Equation 1.

$$w[n+1] = w[n] + 2\mu e[n]I[n] \qquad (1)$$

where $w[n]$ is the coefficient vector, μ is the step size, $e[n]$ is the error vector, and $I[n]$ is the input vector.

E. System Calibration

The parameter that will be investigated in this paper is propagation delay. The desired propagation delay of the input signal is measured from when it enters the system of interest (i.e. human or chest phantom) to the stethoscope. Therefore, when using NLMS to obtain the propagation delay, it encompasses the delay of the data acquisition hardware and must be adjusted accordingly.

The first step was to determine the delay of the signal travelling through the pre-amplifier and back into the computer. In order to do this, the input signal feed back into the pre-amplifier directly. The captured input signal was returned to the computer. NLMS was performed between the input signal and the recovered signal to determine that the preamplifier delay was 10.975ms.

The second stage that the input signal travelled through was into a speaker (subwoofer). Therefore, the total delay includes the laptop computer, pre-amplifier, and the speaker amplifier. These delays were measured using the line out connection of the speaker and feeding the signal into the pre-amplifier. The resulting delay was 0.5ms.

The final stage was to measure the delay of the speaker transducer, funnel, and stethoscope. This was done by placing the stethoscope head directly on the end of the funnel and returning the signal to the pre-amplifier. The delay of all three components was 2.273ms.

Therefore, the total delay of the sound acquisition equipment was 13.748ms. All of the propagation delays that the NLMS algorithm calculated had to be adjusted by the calibration offset. All of the above delays were verified using cross-correlation.

F. Input Signal Selection

The frequency of the input signal defines what frequency information is relevant in the transfer

function of the unknown system. As an example, if the frequency of the input signal spanned from 0 kHz to 22.05kHz and the recovered signal only contained frequency components between 0kHz and 4kHz, much of the lower frequency information would be masked because the transfer function would appear squished due to many frequency components being zero. Figure 3 shows two transfer function plots that were created using measurements from a chest phantom. The plot on the left of the figure uses an input signal with a frequency span as in the example. The other plot has an input signal that has a frequency span between 0kHz and 4kHz. It is evident that with the smaller frequency span, more information (a hidden peak) can be seen in the transfer function and thus this frequency span was chosen for the input signal.

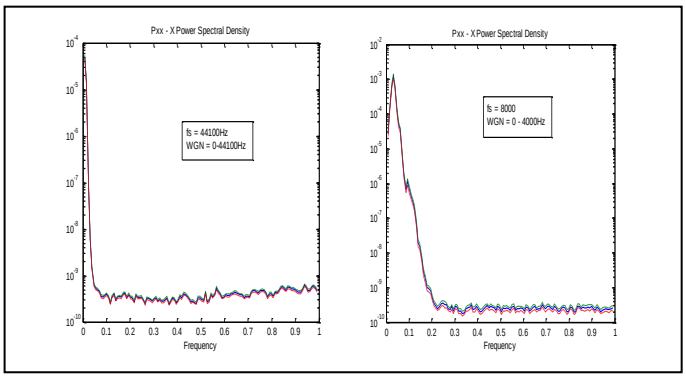

Figure 3: Transfer Functions Obtained from a Chest Phantom Model used to Determine an Appropriate Frequency Span for the Input Signal. The Transfer Function on the Left uses a Wide Frequency Span and makes the Lower Frequency Peak Appear Squished whereas the Transfer Function on the Right uses a Narrow Frequency Span and Reveals a Hidden Peak.

G. Data Processing Software

There were two stages that required the development of software for this project. The first stage was to create a program that could interface with the Firewire port of the computer which was connected to the pre-amplifier. The second stage involved the implementation of the NLMS algorithm to process the recorded data offline. MATLAB was the preferred choice because it had built in functionalities to execute both stages.

H. Chest Phantom Models

A chest phantom is an apparatus designed to simulate the behavior of an actual entity. In this case, a phantom model of a human chest was designed and built in order to perform test cases for the NLMS algorithm and stethoscope array concepts. The model was constructed using camping foam, pipe insulation, a tire inner tube, clear tubing, a syringe, and hot glue. The camping foam was rolled to form a cylinder with a diameter of 0.12 meters and a length of 0.52 meters. The pipe insulation was cut to form two tubes with a diameter and length of 0.04 meters and 0.3 meters respectively. The tubes were inserted into one end of the camping foam at equidistance's from the edge of the camping foam at approximately 0.05 meters. A Y-Pipe was constructed measuring 0.2 meters in length using the remaining pipe insulation and attached to the ends of the tubes. After removing the valve from the tire inner tube stem, the tire tube was slipped over the camping foam cylinder 0.3 meters from the top edge. A 1.8 meter clear piece of tubing with a syringe inserted at one end was attached to the tire stem. Figure 4 illustrates the chest phantom model attached to the sound acquisition apparatus in Figure 4. Notice the stethoscope harness attaches around the tire inner tube. This point is regarded as the chest surface.

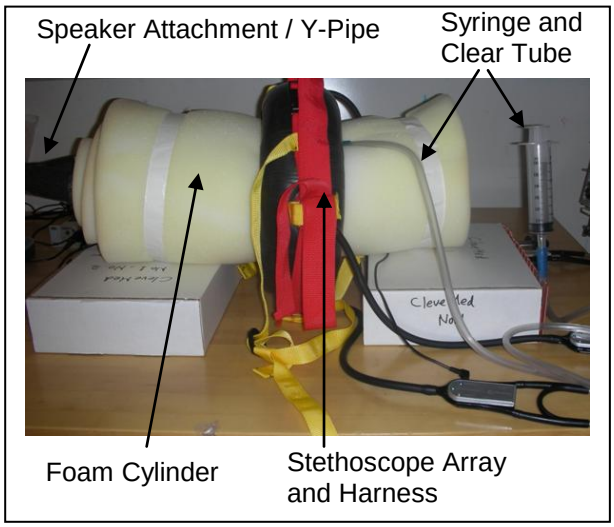

Figure 4: Chest Phantom (Unknown System) with the Stethoscope Array and Harness Attached to the Tire Inner Tube or Simulated Chest Surface

RESULTS

An experiment was performed to test the newly developed instrument's ability to calculate the propagation delay of the input signal from the speaker as it travelled through the chest phantom model. The experimental procedure involved the injection of known volumes of water starting from 0 cc to 30 cc at increments of 5 cc into the tire inner tube of the chest phantom model. The water would immediately drop to the base of the tire tube via gravity and thus enter the sound propagation path of the stethoscope connected to the third channel of the pre-amplifier. This is illustrated in Figure 5 below.

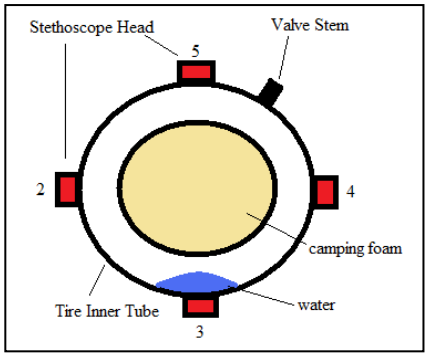

Figure 5: Experimental Setup that Tests the Prototypes Ability to Detect the Propagation Delay of the Input Sound Signal Emitted from the Speaker. The Lower Stethoscope is Connected to Channel 3 of the Pre-amplifier and it is Expected that the Presence of Water should Decrease the Propagation Delay.

The expected result was that the propagation delay of the input signal to the stethoscopes connected to channels 2, 4, and 5 of the pre-amplifier would remain at a constant value and not necessarily the same value due to their varying locations. However, the propagation delay of the input signal to the stethoscope attached to channel 3 of the pre-amplifier would decrease as the volume of water that gathers at the bottom of the tire inner tube increased. This is because the speed of sound in water is much faster than that of the air. Figure 6 shows the propagation delay for the stethoscope attached to channel 2 of the pre-amplifer as being constant. This behavior is also reflected for stethoscopes 4 and 5.

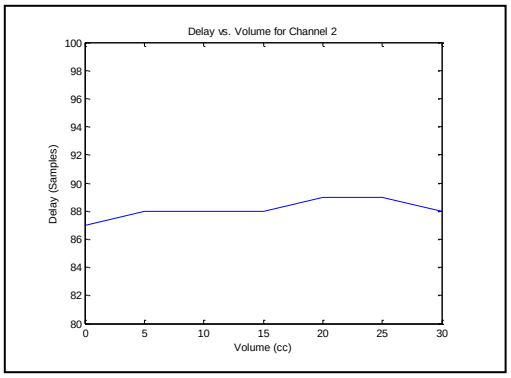

Figure 6: Plot of the Propagation Delay for the Input Signal Travelling Through the Chest Phantom Model to the Stethoscope Attached to Channel 2 of the Pre-Amplifier. Channels 4 and 5 exhibit similar behaviors.

Figure 7 shows that as the volume of water in the inner tube increases, the propagation delay of the input signal through the chest phantom model to the lower stethoscope decreases with a behavior that can be modeled as a decaying exponential. This makes intuitive sense because eventually the lower portion of the tire inner tube will saturate with water and the propagation delay will remain constant.

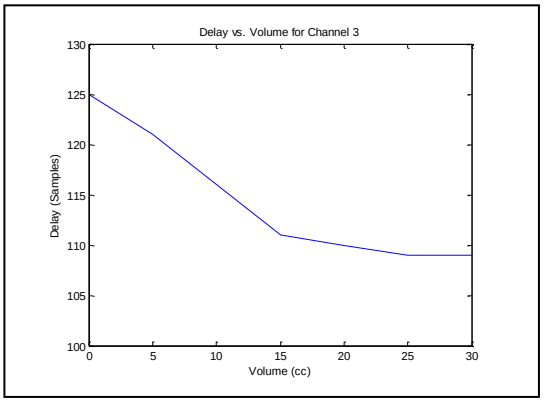

Figure 7: Plot of the Propagation Delay for the Input Signal Travelling Through the Chest Phantom Model to the Stethoscope Attached to Channel 3 of the Pre-Amplifier.

CONCLUSIONS

A novel medical instrument has been described to measure changes in the distribution of lung fluid and lung tissue density. Preliminary results have shown that the system is able to detect changes in the sound propagation delay within a chest phantom model with water having a similar density to that of lung fluids. Future investigations will attempt to define other parameters that will be useful in creating an index to provide physicians with an index rating the effectiveness of treatments administered to patients. We hope to show that this system is a beneficial addition to current lung monitoring technologies.

REFERENCES

[1] J. G. Webster, “Medical Instrumentation: Application and Design,” 3rd Edition, John Wiley & Sons, New York, NY, 1998.

[2] D. Dreyfuss, G. Saumon, “Ventilator-Induced Lung Injury: Lessons from Experimental Studies,” Respiratory Critical Care Medicine, vol. 157, pp.294-323, Copyright 1998