An Electrical Impedance Tomography Analog Front End for Lung Ventilation Monitoring

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Abstract—In this paper we present an electrical impedance tomography (EIT) analog front end implemented with the AMI 0.5um process for monitoring mechanically ventilated patients suffering from Acute Respiratory Distress Syndrome (ARDS). Current injection is accomplished using a digital-to-analog converter (DAC) to save on power and area consumption. The induced differential voltages across subsequent electrodes (controlled by a switching network) are amplified using a programmable gain amplifier (PGA) and digitized using an analog-to-digital converter (ADC) before being sent for further signal processing in a connected computer. Complex impedance mapping is achieved across the entire flow through the use and demodulation of in-phase and quadrature signals.

Index Terms—Bioimpedance, electrical impedance tomography (EIT), lung ventilation monitoring.

I. INTRODUCTION

Acute Respiratory Distress Syndrome (ARDS) is a condition that affects nearly 200,000 patients per year with a mortality rates up to 50% in its most severe cases [1]. For those who suffer from the condition, mechanical ventilation is a common method of treating the symptoms. Inserted into a patient’s mouth or neck, a ventilator aids in inhalation and exhalation through various forms of pressure control. In such applications the presence of a monitoring system is of utmost importance - early versions which lacked this feature posed a higher risk to users as the system themselves may cause ventilator-induced lung injury (VILI) [2]. A current tool in understanding the lungs’ pressure comes in the form of positive end-expiratory pressure (PEEP). However, while this information is useful for controlling the oxygenation of blood, various relationships between PEEP and gas levels remain unclear [3]. In a study using EIT to measure end-expiratory lung impedance changes ($\Delta$EELI), [3] found that increases in $\Delta$EELI rather than PEEP measurements were linked to improved oxygenation. EIT presents a non-invasive method for medical imaging. Compared to CAT scans and MRIs, EIT imaging is portable, low cost, and can monitor in real time, making it especially relevant for monitoring patient ventilation. As further studies find links between lung impedance and ARDS, healthcare providers can better understand the patient’s condition and make adjustments accordingly.

Electrical impedance tomography is an imaging technique which maps the body’s interior impedance distribution via electrode measurements on the skin. From a measurement standpoint, EIT follows the same principles as bioimpedance measurements. A low amplitude current is injected through the thorax across a series of electrodes and the corresponding surface potentials are measured. This information allows the extraction of the real and complex impedances of the surface measurements to be mapped into impedance fields using techniques such as finite element modeling (FEM) [4].

II. SYSTEM ARCHITECTURE

The system-on-chip (SoC) is comprised of three main blocks: a voltage readout circuit, a current stimulator, and an array of electrode switches.

A. Current stimulator

The proposed system relies on using a differential DAC as opposed to a voltage-controlled oscillator (VCO) for generating the sinusoidal stimulus signal. In [5] it was shown that a system implementing a combination of a DAC and look-up table (LUT) provided a significant reduction in power consumption and layout area compared to an earlier system using an OTA-based sinusoidal generator [6]. Generating a sinusoidal output using a DAC, however, requires a sufficiently high resolution to avoid generating large frequency components outside of the fundamental frequency. From MATLAB simulations sampling at 10 times the signal frequency, it was found that the power spectral density (PSD) of an ideal 8-bit DAC has a third harmonic at -58.6 dBc whereas a 6-bit DAC’s third harmonic was at -38.6 dBc. The PSD of the 8-bit DAC was deemed sufficient as the unwanted frequency components will be additionally attenuated using filters.
The sinusoidal voltage output of the DAC is then fed into an in-phase/quadrature (I/Q) generation circuit which will produce a differential output \( V_I \) which is in-phase with the input and \( V_Q \) which is 90° out of phase. The I/Q signals will be used in the sensing path to determine the phase of the measured impedance.

Next, the sinusoidal signal is sent to an operational transconductance amplifier (OTA) to convert the differential voltage into a current stimulus. That current passes through a switching network and applies the stimulus to the target electrode. The electrodes intended for use in this application are of the thin-film capacitive type and were chosen due to their ease of placement and preparation.

### B. Voltage Sensor

Once the stimulus current is delivered, the system will read the voltages across pair combinations of the other electrode. In order to adequately read the input signal which may be on the order of microvolts, the potential difference is fed through a low-noise instrumentation amplifier (INA) with high common-mode rejection ratio (CMRR). Low-frequency non-idealities such as DC offset and 60 Hz ambient interference is rejected via high-pass filter. Since the original voltage may vary greatly in magnitude between \( \mu \)V to mV, the signal must also be delivered into a programmable-gain amplifier with adaptive control to prevent saturation and ensure the signal is still detectable [7]. Using the signals from I/Q generation circuit, the signal is then demodulated and sent to ADCs. One ADC is used for each I/Q path. Since the value of the gain setting of the PGA is available to the digital controller, an 8-bit ADC will for sufficient to attain adequate resolution. The digital outputs of the ADCs are sent to the digital controller and eventually will be used as measurement values.

### C. Digital Controller

Considering the heavy computations involved with FEM models, it is necessary to do processing off chip. Benefits of interfacing to a computer rather than a microprocessor include faster deployment of new EIT algorithms and accessibility for healthcare providers to incorporate the system into their workflow. To bridge the transition from analog to digital signal processing, a digital controller is needed to interface the SoC to a computer through USB. Although the focus of this work is on the analog front end (AFE), it is important to consider what blocks should go into the digital controller. Shown in Fig. 2, the controller needs control logic for the DAC, ADCs, PGA, switching network, and clocking. The proposed system is intended to receive power through the USB connection. Most ports are capable of supplying 5V up to 500 mA or more which is more than sufficient for this application. To ensure the integrity of the supply voltage the design will include voltage regulation.

### III. Performance Summary

#### TABLE I: Comparison with State of the Art

<table>
<thead>
<tr>
<th></th>
<th>This Work</th>
<th>Lee [6]</th>
</tr>
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<tbody>
<tr>
<td>Supply Voltage</td>
<td>3V</td>
<td>1.8V</td>
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<tr>
<td>Power Consumed</td>
<td>Unknown</td>
<td>4.84 mW</td>
</tr>
<tr>
<td>Frequency</td>
<td>10 kHz</td>
<td>10 - 360 kHz</td>
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<tr>
<td>Current drive</td>
<td>1 mA(p-p)</td>
<td>0.125-0.5 mA(p-p)</td>
</tr>
<tr>
<td>Resolution</td>
<td>8-bit ADC/DAC</td>
<td>Not specified</td>
</tr>
<tr>
<td>Clock</td>
<td>100 kHz</td>
<td>Not specified</td>
</tr>
</tbody>
</table>

### IV. Division of Labor

#### TABLE II: Projected Responsibilities

<table>
<thead>
<tr>
<th>Team Member</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaehoo Choi</td>
<td>INA, OTA, PGA, switching network</td>
</tr>
<tr>
<td>Xiaoshan Wang</td>
<td>DAC, I/Q Gen.</td>
</tr>
<tr>
<td>Daniel Zhang</td>
<td>ADC, I/Q Demod.</td>
</tr>
</tbody>
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### REFERENCES


