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Design and Characterisation of an EIT Voltage Conditioning Module

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Abstract: Electrical Impedance Tomography is used to image the cross-sectional conductivity of an object. It is clinically used for high-frame-rate imaging of lung ventilation. Most current systems use very limited current injection waveforms and patterns. We have developed a flexible system for researching alternatives. This paper covers our voltage conditioning module's design and characterisation. The device was shown to work up to the desired 10 MHz. The responses were uniform with minor gain mismatch between all channels after manufacturing variations. The low-frequency (<1 MHz) crosstalk is on the order -55 dB, and the worst cases around 8 MHz are around -35 dB.

Keywords: EIT, Electronic Design, Analog Design.

1 Introduction

Electrical Impedance Tomography (EIT) is a soft-tomography technique used to image the impedance of a cross-section of a conductive object using a circumferential electrode array; however 3D implementations also exist. It can be very compact, relatively inexpensive, and provides high frame rates, compared to more mainstream methods like CT and MRI, and also does not require strong magnetic fields or ionizing radiation; however the image resolution is much lower. This is clinically used for imaging lung ventilation; as it can provide more information to respiratory therapists, like regional collapse, than one-dimensional values like lung compliance calculated by traditional respirators [1].

The general imaging methodology creates frames of data. In each frame a number of electrode pairs are sequentially used to inject current, while the voltages are read on the remainder of the electrodes. Typically an AC current with fixed frequency around 100 kHz and less than 1 mA is used, and a fixed/constrained pattern of electrode pairs for current injection are used (e.g. only adjacent or opposite electrodes). The voltage data is recorded and used to mathematically reconstruct an image of the conductivity of the object cross-section.

Using higher frequencies, multiple frequencies simultaneously (multi-frequency-EIT or MF-EIT[2]), and different stimulation patterns may allow more information to be extracted from the recorded voltage signals. Doing so may improve the achievable resolution, or achieve other goals such as tissue differentiation due to different spectral impedance characteristic (e.g. better differentiation of fat vs muscle, or cancerous vs normal tissue).

We have developed a research-oriented system for EIT measurements. This is based around 4x 8-channel 100 MSa/s 14-bit digitizers (Keysight M3100A) for 32 channels of voltage measurement, and a 4-channel 500MSa/s 200 MHz 12-bit AWG (Keysight M3100A) for current signal generation. The aim is to be flexible with both the stimulation pattern (any pairs of electrodes), and the stimulation signal (bandwidth up to 10 MHz, arbitrary signal/multi-frequency); and the parallel full-waveform recording of all channels should give maximum flexibility for signal acquisition and processing. This flexibility should open opportunities to research new methods in EIT measurement and reconstruction. The current signals (voltage signal from AWG) will be processed by an V-I converter and multiplexed to the 32 electrodes by a current supply module that is outside of the scope of this paper.

As the voltage signals from the electrodes have a low power/high impedance, we developed a voltage conditioning module to sit between the electrodes and the digitisers to buffer and amplify the signal. Each module handles 8 electrodes/channels. This basic design and initial characterisation of this voltage conditioning module will be discussed in this paper.

Bandwidth up to 10 MHz is desirable as the conduction is still mostly ohmic, with a current distribution described by the Poisson Equation. This allows existing EIT reconstruction methods to be applied. Above this frequency the magnetic effects become significant requiring a reconstruction that considers the more complex Maxwell Equations. Future research using our developed hardware will seek to quantify if the full bandwidth to 10 MHz is practically useful (e.g. spectrally differentiating tissue types, or improving SNR/resolution).

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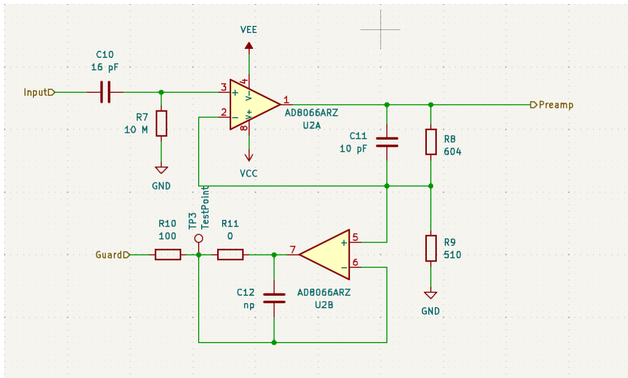
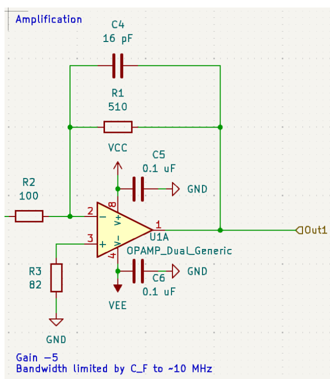


(a) Pre-amplifier and driven guard.



(b) Amplifier.

Fig. 1: Schematics of relevant parts of voltage conditioning circuit.

2 Methods

2.1 Design

The primary functions of the voltage conditioning modules are to buffer the high impedance input signals, and amplify them before passing them to our Keysight digitisers, as well as provide an output for the driven guard circuit used to lower the effective capacitance of the electrode cables.

The pre-amplifier design and driven guard are shown in Figure 1a. The input has a simple RC high-pass filter to exclude DC bias, with a -3 dB frequency of 1000 Hz. This feeds into an AD8066 which was selected for its low input bias current, and high bandwidth. This amplifier is set with a gain of 2.18 after simulating with parasitic components, to aim for an overall gain of 2 after other expected losses occur. A 10 pF capacitor was added into the feedback to improve stability. The driven guard used the same AD8066 op-amp, however the low input bias is likely not a critical concern and it is an opportunity for future cost optimisation. A 100 Ω output resistor was added for stability after simulating with cable capacitance; and a non-populated space for a feedback capacitor and jumper were used to allow flexibility in case of issues after manufacturing and testing.

The amplifier stage in Figure 1b is used to further boost the signal without so much concern for the input bias. An AD8274 op-amp was used for its bandwidth (low input bias was not so critical outside of the preamplifier). An inverting amplifier was used with an additional 16 pF feedback capacitor for stability. The gain of -5.1 combines with the pre-amp gain of ≈2 to give an overall expected gain of about -10.

These stages were repeated 8 times on each voltage conditioning module PCB. Thicker traces were used for the input signals to the pre-amplifiers, although in hindsight thinner traces may reduce parasitic capacitance and allow more shielding between channels.

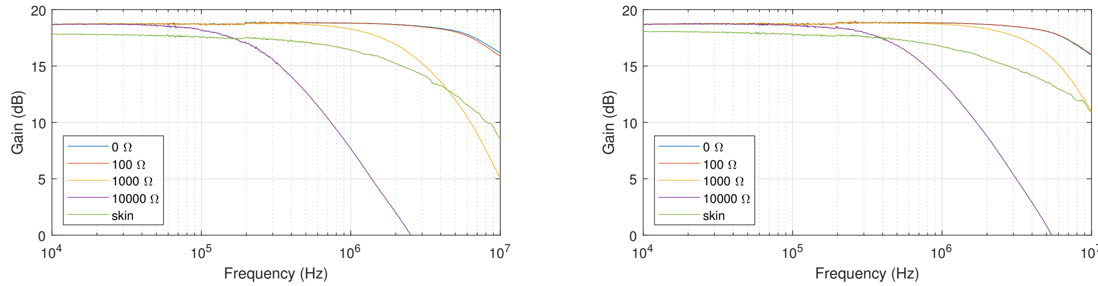
A 26 pin connector is used to connect the electrode cable to the PCB, giving a Signal, Guard, and Ground connection for each channel, with 2 unused pins on the end. Another 26-pin connector on the PCB with the same pinout (except replacing guards with grounds) is used to connect the voltage conditioning module to the central current supply module, in this case the 2 extra pins are used for +5 V and -5 V supply from the current module. This allows the current module to also inject current on the voltage measurement electrodes, or by plugging into a power-only connector on the current supply module, the voltage and current electrodes can be separated. The common pinout facilitates swapping the same electrode cables between these configurations.

The 16-pin connector on the end of the board is used to connect the voltage outputs to our Keysight digitisers through an adapter board that 8 SMA coaxial cables will plug in to. This allows the voltage modules to be quickly disconnected without having to unscrew 8 SMA connectors each time. The connector pinout is designed to be reversible so the adaptor PCB can either overlap the top of the voltage module for compactness, or go extend out over the side to allow access for probing during operation.

2.2 Characterisation

Three main things were tested for: overall bandwidth/response with different input impedances, response/consistency of all channels, and the crosstalk between channels and cables.

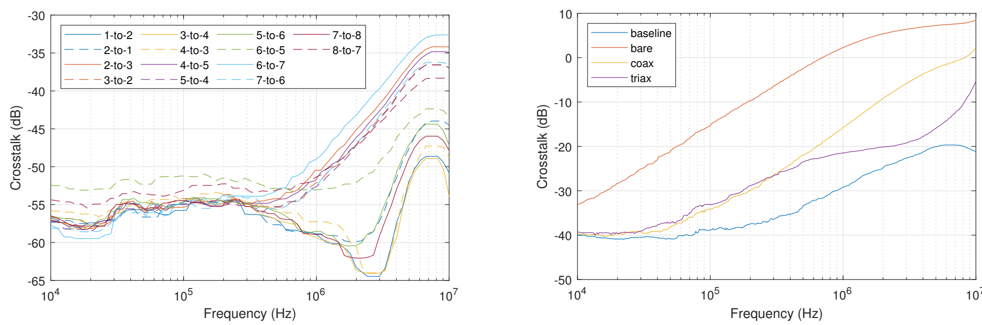
Overall bandwidth was tested using a Digilent Analog Discovery 2 with the network analyser function. 100 mV amplitude input was used and applied to the input of channel 1 on a voltage conditioning module through a resistor to control input impedance. The output was measured to get the overall response of the channel from 10 kHz to 10 MHz. A line is plotted for each resistor value tested, and additionally the frequency-dependant skin/electrode impedance was simulated



(a) MUX/current board connected.

(b) MUX/current board isolated.

Fig. 2: Response of voltage board with different input impedances.



(a) Crosstalk between all adjacent channels on one board.

(b) Cross talk increase with different cable types.

Fig. 3: Crosstalk between channels and effects of different cables. Recipient channel grounded with 1 kΩ resistor impedance.

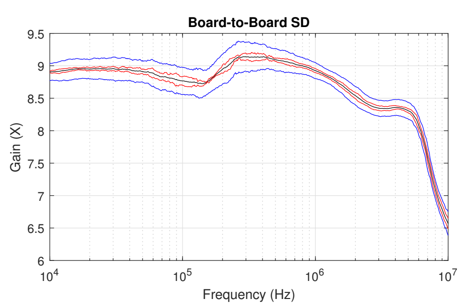


Fig. 4: Comparison of average responses between boards.

by pinching two wires 1 cm apart with moistened fingertips. This was also tested with the voltage board connected to or isolated from the multiplexor outputs of the current supply board.

Consistency was measured by testing the input-output response of all 8 channels on the 4 voltage conditioning modules we assembled. The responses for all channels on each board are compared, as are the average responses between boards.

Crosstalk between channels was similarly tested, but the stimulation was provided to one channel and the output of the adjacent channel was measured. In this case the input of the recipient channel was grounded with a 1 kΩ resistor to simulate the output impedance of skin; however this is conservative as the crosstalk was worst at higher frequencies above 1 MHz where skin impedance drops closer to 100 Ω [3]. Crosstalk was measured for all adjacent channel combinations on one board, and also using one channel to compare crosstalk from 70 cm of taped-together parallel cables, either unshielded/bare wires, coaxial, or triaxial.

3 Results & Discussion

The overall bandwidths with different frequencies and either connected to or isolated from the current multiplexors are shown in Figure 2. It is clear that higher input impedances reduce the bandwidth, especially when the multiplexors' parasitic capacitances are present. However as the contact impedance of skin greatly reduces as frequency increases, the realistic response of skin is only partially attenuated before our 10 MHz goal, which is also shown in Figure 2; and with appropriate calibration/compensation this signal level should be easily sufficient up to 10 MHz. It is also noted that the skin response is generally lower in the plot because

Tab. 1: Crosstalk over different frequency intervals.

Pair	Avg. Interval (MHz)		Pair	Avg. Interval (MHz)	
	0.01-1	6-9		0.01-1	6-9
1-to-2	-56.4	-48.7	2-to-1	-56.3	-44.1
2-to-3	-54.8	-34.4	3-to-2	-55.0	-36.6
3-to-4	-56.2	-49.3	4-to-3	-55.1	-47.4
4-to-5	-55.0	-35.0	5-to-4	-55.4	-36.6
5-to-6	-55.6	-44.5	6-to-5	-52.2	-42.4
6-to-7	-54.5	-32.9	7-to-6	-55.6	-36.3
7-to-8	-56.0	-46.0	8-to-7	-53.4	-38.4

of voltage divider effects due to ground leakage through the body.

The crosstalk between all adjacent channels on one board, and for the different cables test, are shown in Figure 3a. The channel crosstalk figures are also summarised in Table 1. Below 1 MHz the crosstalk is relatively constant, possibly due to the noise floor of the measurement; hence the true crosstalk may be less in this range and further, more careful, measurement is required. After 1 MHz, the crosstalk increases with a similar slope for all channels, however the peaks are not equal. The worst-case crosstalk is measured at 6-9 MHz, however this is beginning to exceed the rated bandwidth of the Analog Discovery. Of note is that each channel pair does not have equal crosstalk in both directions; this is likely due to the non-symmetric active components in the circuit as implemented on the PCB.

The cable crosstalk in Figure 3b also shows the advantages of triaxial cable over coaxial or unshielded wires. Without the driven guard circuit the coaxial/triaxial would increase capacitive leakage on the input and reduce bandwidth, however with our driven guard implementation this is not a significant issue.

The amplifier responses for all channels on all boards are summarised in Figure 4. The comparison of average responses for each boards shows a high degree of consistency between boards. The standard deviations of the measurements for each frequency shows a variation in total gain for all channels of about $\pm 5\%$, which should be easy to simply calibrate away.

4 Conclusion

An 8-channel voltage conditioning module was designed for a research EIT device.

The device was shown to work up to the desired 10 MHz. The responses were uniform with minor gain mismatch between all channels after manufacturing variations. The low-frequency (<1 MHz) crosstalk is on the order -55 dB, and the worst cases around 8 MHz are around -35 dB.

Author Statement

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