Electrical Impedance Tomography for pulmonary oedema extent monitoring: review and updated design

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Electrical Impedance Tomography for pulmonary oedema extent monitoring: review and updated design

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Abstract. Monitoring pulmonary oedema would be greatly facilitated by the availability of a graphical representation of its size and density to guide therapeutic interventions. Currently the clinician has only indirect estimations because X-ray imaging or computed tomography can not be repeated often. To avoid the transfer of critically ill patients and to have continuous information Electrical Impedance Tomography (EIT) is suggested. Circuit designs for EIT are reviewed, including wave generators, current sources, differential amplifiers, synchronous voltmeters, multiplexers and control modules. Nine designs are studied, the characteristics of five of them are presented (England 2005, Uruguay 2002, Iran 2006, China 2007 and Switzerland 2012). Three different solutions are compared (components cost range from) and an optimal design is proposed which includes a direct digital synthesizer (DDS) for signal generation, a modified Howland configuration for current source, 16 bits for the analog to digital conversion, and a digital signal processor (DSP) for the synchronous demodulation as well as to process the measurements for the reconstruction algorithm. This allows us to design low cost, gross graphical representations for oedema extent monitoring, with little anatomical accuracy.

1. Introduction

Treatment of pulmonary oedema is based among other parameters upon the estimation of alveolar volume occupied by liquid. The injection of high frequency current ($> 20kHz$) at amplitudes not perceived by the human body (of the order of $2mA$) and the resulting measurements of voltages on the chest's skin, allow to estimate the electrical impedance. This estimation can be dispayed as a tomographic image. The method, known as Electrical Impedance Tomography (EIT), low-cost, non-invasive and prolonged application to show a low resolution image of the distribution of fluid in the lungs and its evolution. Is thus an attractive alternative to X-rays and other cumbersome procedures

Since the pioneering work of Barber and Brown in 1984 [1], the last two and a half decades have seen a considerable growth of EIT applications in research centers, with few commercial offers. Since 1995 the Núcleo de Ingeniería Biomédica (nib) has developed circuits [2], reconstruction softwares [3] and complete prototypes [4, 5] under the name of IMPETOM (**impe**dance **tom**ography) with test results in phantoms and healthy volunteers.

This paper presents the evolution of EIT designs adopted, as published in English literature.

2. EIT hardware architecture

The different blocks of an EIT system are the following:

- Waveform synthesis
- Current source
- Differential amplifier
- Synchronous voltmeter
- Multiplexers
- Control block

Figure 1 shows the architecture of a typical EIT system.

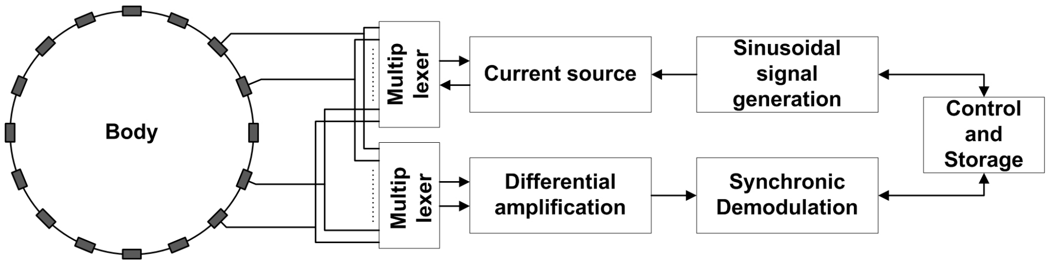

Figure 1. EIT system basic block structure with a differential current source. There are 16 electrodes affixed onto the skin of the patient's body

2.1. Waveform synthesis

The wave generator makes the reference signal for the sinusoidal current source,besides generating the synchronizing signal to be used by the demodulator. There are analog and digital solutions, the latter being the most commonly used in recent developments such as the circuit described by Saulnier [6]. These solutions feed a digital-analog converter with stored samples. The performance of this unit is measured in terms of spectral purity and its signal to noise ratio (SNR).

2.2. Current source

The current source is driven by the wave generator signal to convert it into a current to be injected into the body through the electrodes. You can use single-ended or floating sources. The former are ideal for systems with multiple sources, while the latter are used on systems with a single source [6]. The proposed solutions for the current source are varied, mostly using discrete op amps or transistors, but all eventually face the same problem: the output impedance is difficult to maintain high [6]. This impedance consists of an output resistance and stray capacitance: the output impedance thus affects the value of the injected current, but not always in the same way, as it depends on the load seen by the source, in this case the human body (and the electrode interface skin), which is constantly changing. That is why the design of the source must take into account load variability in order to obtain an output impedance that allows the current to vary at most within an acceptable range. Ideally, this range should not exceed the precision of the system in terms of A/D bits [6]. One may also measure the actual current being injected and to reflect it in the reconstruction algorithm.

2.3. Differential amplifier
Either differential or single-ended voltages may be measured in principle, but the vast majority of systems adopts differential configurations that result with a reduced dynamic range of the voltages [6]. Designers face here a second problem to solve: the common mode voltage of the amplifiers. To reduce it, the components and the operating point must be chosen very carefully. In addition to this, one may use specific techniques, such as an additional electrode located away from the area where the measurement is taken to reintroduce feedback current much in the same way as the ECG driven-right-leg circuit (Webster) [6].

2.4. Synchronous voltmeter
To reconstruct a tomographic image it is necessary to take phase-sensitive voltage measurements, either to measure the resistivity and permittivity, or just the resistivity. This is why it is necessary to have a coherent signal from the wave generator. One can perform this demodulation in either the analogue or digital domain, the latter being the most used recently [6]. One way to perform the digital demodulation is via an A/D which converts the input analogue signal to digital samples which are then multiplied by sine or cosine functions of the same frequency. Then the samples are integrated over a number of cycles of the original wave as described by Saulnier [6], to obtain a value used in the algorithm.

2.5. Multiplexers
The multiplexers are needed in systems with a single current source or with fewer voltmeters than electrodes. Multiplexers are used to select channels through which current is injected and where the voltage is measured. The multiplexers have non ideal characteristics that create problems in the system, as the on-resistance, and above all, the input and output capacitances.

2.6. Control and data storage block
Control is necessary to synchronize all other blocks, to store the measured data and to transfer it to a computer that will perform the image reconstruction. Depending on the complexity of this block, the options are varied, from basic microcontroller [7] to high performance DSPs (digital signal processors) [8, 9, 10, 11] in order to make a more complex pre-processing of the data.

3. Literature review method
We searched the literature on EIT systems, excluding publications solely related to reconstruction algorithms, therefore not including hardware information. Selected publications contain descriptions of circuits used, and were published from 2004 to 2012. The previous study by NIB was concluded in 2004, and therefore the publications prior to this date are analyzed in the documentation of these projects [2, 3, 4, 5]. In the present analysis we also included the characteristics of IMPETOM [2, 3, 4, 5] to compare it with newer equipment.

The search yielded seven publications by five groups, that along with the solutions for IMPETOM, allow us to identify trends in design and performance of EIT systems.

4. EIT projects
Ferreira, Rodriguez and Simini proposed in 2002 [2] a circuitry for electrical impedance tomography with sinusoidal signal generation using the Function Generator MAX038 (Maxim). The current source includes the operational amplifier AD844 (Analog Devices). Two multiplexers MAX336 (Maxim) select the electrodes that carry the current. In the measurement stage, 16 identical circuits avoid the use of a multiplexer. The INA114 (Burr Brown) functions as an instrumentation amplifier and the output is fed to a bandpass filter made with the MAX274

chip (Maxim). A sample and hold circuit captures the filter output with the LTC1043 (Linear Technology) IC.

Gonzalez, Liguori, and Simini in 2005 [4] designed a prototype to integrate with the previous project, developing the control stage and the analog to digital conversion through the PC-LPM-16PnP (National Instruments) board, which has 16 input channels and 12-bit resolution converters. The results measured by [2] show a SNR (signal to noise ratio) of $40dB$, CMRR (common mode rejection ratio) in the order of $50dB$ and a current source output impedance of $560k\Omega$ at $50kHz$.

Wang, Liu and Wang in 2005 used a DSP [8, 9] for control and data preprocessing, the DSP used is the TMS320F206 (Texas Instruments). A VCCS (voltage controlled current source) generates the signal that is injected by the electrodes. For measuring voltages, a multiplier is implemented with the AD734 (Analog Devices) IC, A low pass filter with the MAX275 chip (Maxim), and the ADC used is the AD1674 (Analog Devices). The results are oriented to rebuild times, reaching a rate of more than thirty frames per second.

Soleimani in 2006 [12] showed a low-cost equipment for reconstruction in 2 dimensions. The signal is digitaly generated, using an EPROM (27C258) to storage a sinusoidal of $23kHz$. A counter reads the data from the EPROM and feeds a DAC (DAC-0808 National Semiconductor). Harmonic distortion was measured in 1.3%. This signal is fed to a buffer which in turn is connected to a VCCS, performed with the operational AD644 (Analog Devices). For measuring the voltage, synchronous demodulator is used due to its ability to remove noise. It uses the AD625 instrumentation amplifier (Analog Devices) as the input stage before the acquisition card PCL-812PG I/O (Advantech).

Xu et al. created in 2007 a system [10] using 128 electrodes for three-dimensional images of the human thorax. A multiple frequency current is injected using the IC AD9852 (Analog Devices). The frequency range is from $1kHz$ to $2MHz$. The control module is implemented with the chip TMS320F2812 (Texas Instruments). The multiplexer MAX306 (Maxim) is used. For the acquisition of data the integrated AD624 (Analog Devices) is used as a pre-amplifier, then a fourth-order Butterworth filter is implemented with the integrated MAX275 (Maxim). The synchronizing signal is taken from the AD9852, and a synchronous demodulator is implemented in the DSP. As conclusion, reconstructed images are shown, but they don't provide hardware performance data in the form of SNR or any other form.

Bera and Nagaraju developed in 2009 [13] a system to study calibration. For current injection they use a VCO (voltage controlled oscillator) built with the MAX038 (Maxim), which feeds a modified Howland type current source [6]. This module is constructed with two operational amplifiers AD811 (Analog Devices) and generates current of $1mA$ and $50kHz$. A differential amplifier stage and a filter is used for the voltage measurement. Then the resulting voltage signal is measured with a multimeter and a digital oscilloscope. A central electrode is used to reduce the common mode signal. The results show that the common mode is reduced to a maximum of $67mV$.

Hamidi et al. implemented in 2010 [11] a synchronous demodulator with a DSP (Texas Instruments MS320C6713) which is mounted on the development board TLV320AIC23(Texas Instruments). This board has two 16 bits ADCs (AIC23 Texas Instruments) with a sampling rate of 96 kbps. With simulated data, the system had an error in the phase of 0.12 degrees and a signal to noise ratio (SNR) of $130dB$. Using a phantom, the results were worse, but still significantly good.

Gaggero et al. in 2012 [14] developed a system to address two important problems affecting the reliability and usability of electrical impedance tomography. These are: a) EIT is very sensitive to the contact impedance of the electrodes, which can be very large and vary over time due to movement. b) The difficulty of placing the electrodes individually. To solve these problems they implemented a method of active electrodes, which uses a voltage buffer physically close to the electrodes. This stabilizes the contact impedance, and also using a multiplexing method reduces the wires from the electrode belt to the central block. In the central block of the equipment is the signal generator, power source, the electrode handling and the communication with the PC. For this, two boards are used: an Altera Stratix II development kit (Altera) that has integrated the AD9433 ADC (TI), the DAC904 DAC (TI) and Ethernet inteface. Another custom board is responsible for the analog stage, it has a differential amplifier and high pass filter implemented with an AD8221 (Analog Devices) then converts the signal into a differential signal and performs a low pass filter with the integrated THS4502 (IT). The sinusoidal signal is generated in the FPGA through a numerically controlled osciliador (NCO), and a modified Howland circuit is used as a current source. The results shown are the output resistance of current source, and provides that for lower frequencies, this resistance will be lower.

Dixtal Biomedical developed a commercial system, and seen in operation in Montevideo in 2010, called DX 1800, which provides real-time chest images. It has two modules: the DX1800 itself, and a monitoring software that runs on a computer. The DX 1800 is the system responsible for the current generation, voltage measurement and data processing, this system has 32 electrodes to be placed in a line around the patient's chest. The software handles the user interface and display the reconstructed images. The connection between modules is performed via an Ethernet connection. Because it is a commercial system, it was not possible to know how the different blocks are implemented.

Another commercial system is the PulmoVista 500 of **Dräger Medical** [15] to display the distribution of ventilation. It has a processing block and a screen showing the ventilation in the lungs and various respiratory measures. A belt with one row of 16 electrodes is placed around the chest and injects currents between $80kHz$ and $130kHz$, generating images with a rate of 10 to 30 per second with a resolution of 1440 x 900 pixels.

Table 1 presents the summary characteristics outlined for the most representative systems, taking the published figures and extrapolating information wherever possible.

5. Design Options

Using the information from the previous projects, we consider three feasible options for the IMPETOM hardware, one option corresponding to a completely analog signal processing, the other two using a digital signal processor. These are analyzed based on cost factors, difficulty of assembly, performance and speed.

5.1. Discrete components without digital processing

The first option is to design a system using discrete components without a digital signal processing, this would include a basic microcontroller (eg ATmega168, Atmel, $ 3.33) which is responsible for control and synchronization of different blocks. In this, the demodulation of the signals would be carry out using discrete components, also the filtering and gain stages. Where possible, we use analog-digital converters (A/D converters or ADCs) to digitize the signals and send them to the computer for image reconstruction. Another option derivative of this solution is to use a data acquisition card as used in the project IMPETOM [4], these cards would provide the A/D and communication with the computer. A precondition for improving system performance with respect to the previously developed is to use at least 16bit ADCs resolution. These data acquisition card (DAQs) have multiple input channels, making it possible to have a channel for each pair of electrodes, enabling measure in parallel, this also means build 16 input channels, such as those by IMPETOM C [2], increasing the cost and difficulty of design, in addition, that these DAQs use many input channels makes them very expensive, such as the NI USB-6211 (National Instruments) having a minimum cost of $690. The main problem with this solution is to repeat the same mistakes in IMPETOM C, obtaining a system where the electrical noise

Table 1. Comparative characteristics of circuits for Electrical Impedance Tomography.

	Sheffield system England 2005 [16]	IMPETOM C Uruguay 2002 [2]	Open acces Iran 2006 [12]	128 electrodes system China 2007 [10]	Active Electrodes Switzerland 2012 [14]
Waveform synthesis	Look up table in ROM	Function generator	EPROM 27C258, VCCS(AD644)	DDS AD9852 (Altera)	Altera Stratix II (NCO) DAC904
Current source	floating with transformer	AD844	current generator $5mA$, $23kHz$		Modified Howland
Multiplexer	2 multiplexers 1 to 16 AD DG506	2 multiplexers 1 to 16	IC-4067 multiplexers	16 MAX306 multiplexers	
Differential amplifier	Instrumentation amplifier INA 110	Instrumentation amplifier INA 114	Instrumentation amplifier AD625	Pre-amplifier AD624 with 4 order lowpass filter MAX275	AD8221 + THS4502
Demodulation	Phase-sensitive voltmeter	LTC1043 sampler	Synchronized pulse demodulation	Synchronic demodulation	Digital Demodulation AD9433
Processing	External computer	IMPETOM I [3]	I/O card ADVANTECH PCL-812PG 16bits	High speed DSP TMS320 F2818	Altera Stratix II

and the imperfection of discret components dominate the measurements obtained, making it impossible to get a reasonable image. The advantage is the cost, table 2 shows the cost of the most notable components of the system, the total shown does not reflect the cost that actually could have this solution, as it ignores many minor components, like resistors, capacitors, crystals, connectors, etc. which increases the final cost.

5.2. Evaluation Board

To minimize the processing of signals in analog form, they must be passed as soon as possible for the A/D converters and perform as much processing in digital format, this would be after a basic first filtering and gain stage, the signals are then processed by a Digital Signal Processor (DSP), both in the filtering phase and in demodulation and for obtaining the amplitude and phase of the signals. This option gives a great flexibility to the system, allowing suit the system to different uses, such as measuring both resistivity and permittivity, also to reduce appreciably the errors introduced by the use of discrete components, and the processing speed ensures the final speed of the system to reconstruct the images won't be affected. By using a DSP, the system transmit to the computer the measurement vector ready to be used in the reconstruction

Table 2. Cost of EIT hardware designed with discrete components.

Block	Design	Component	Quantity	Price, each, U$S
Signal Generator	DDS	AD9832	1	11
	Multiplier DAC	DAC8811	2	13
VCCS	Operational Amplifiers	OPA602	2	10
Current Measurement	Digital potentiometer	AD7376	1	8
Multiplexers	Multiplexer	ADG406	4	12
Amps., filtering	Differential Amps.	INA114	4	12
	Programmable gain amps.	PGA203	2	17
Synch. Demod.	Discrete components	AD630	2	25
Control	Microcontroller	Atmega168	1	4
	Memory	M48Z129V	1	27
	ADC	AD7892	2	23
			Total	**322**

Notes: DDS: Direct Digital Synthesis, DAC: Digital to analog converter, VCCS: Voltage controlled current source, ADC: Analog to digital converter.

method.

Two paths can be taken to use DSPs, the first is an Evaluation Board or Starter Kit, examples of this are the Starter Kit TMS320C6713 (IT, $ 395) or the Evaluation System ADSP-BF533 EZ-Kit (Analog, $ 490). These systems are aimed at evaluation or initiation of the engineer in the use of a DSP model and tools developed, often for teaching purposes. It is not the purpose of these boards be used in commercial products. The advantage of using these boards is to have a complete system that contains the DSP, memory, demodulators including the A/D and programmable gain amplifiers (PGAs), communication with the computer, ports for general use, the circuit to program the DSP, this arranged in the most optimal way to get results soon from the start. Figure 2 shows the block diagram for a system implemented with an evaluation board. Figure 3 shows the block diagram of the card TMS320C6713 SDK.

The disadvantage is that being this boards a fixed set of components, some of them couldn't adapt to the problem being solved, in fact, most of these cards, at least those found in a price range between $ 300 and $ 600, are designed to work with audio, then the A/D and PGAs are within a codec (AIC23 IT in the TMS320C6713 [17]) specifically designed for audio, this doesn't exclude the use of this boards for EIT systems, there are systems implemented with very similar boards ([18], [11]) but it is necessary to adapt to certain limitations, the most notorious is that this codec operates at frequencies used in standard audio processing, the higher sampling frequency being $96kSPS$ (samples per second,) by the Nyquist theorem, this limits our system to work at frequencies below $48kHz$, although to get really good SNR values, operating frequency must be still smaller, below $20kHz$; this increases the total time required for the acquisition of the signals, in addition to some under-use the DSP that is designed to operate at very high speeds (the DSP within the TMS320C6713 has the same name and operates at $225MHz$ and can perform 1350 million floating point operations per second [19].) Another disadvantage is the cost, again Table 3 will present costs of the more noticeable component to use, and a estimated total cost where we have to take into account the same observations that were made for the table above, in this case the difference between this cost and the real final cost is a little lower than the case of using discrete components, since the board brings all the components needed for the entire system to function properly.

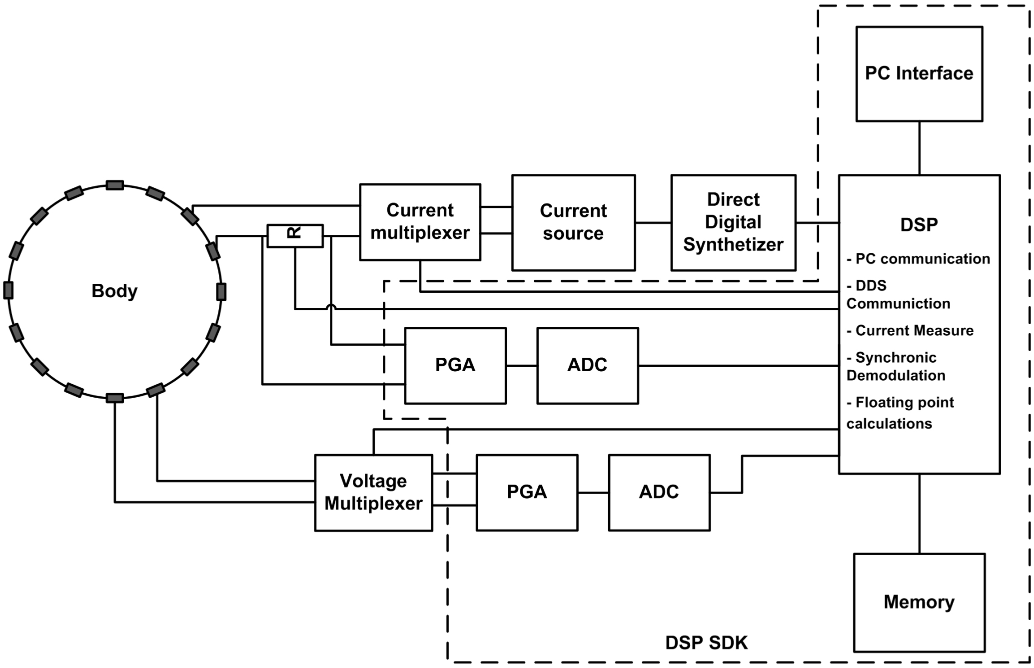

Figure 2. EIT hardware using an Evaluation Board.

Table 3. Cost of EIT hardware based on a DSP Evaluation Board.

Block	Design	Component	Quantity	Price, each, U$S
Signal Generator	DDS	AD9832	1	11
	Multiplier DAC	DAC8811	2	13
VCCS	Operational Amps	OPA602	2	10
Current Measurement	Digital potentiometer	AD7376	1	8
Multiplexers	Multiplexer	ADG406	4	12
Amps, filtering				
Synch. Demod. Control	DSP EB	TMS320C6713	1	395
			Total	**508**

Notes: DDS: Direct Digital Synthesis, DAC: Digital to analog converter, VCCS: Voltage controlled current source, DSP: Digital signal processor, DSP EB: DSP Evaluation board.

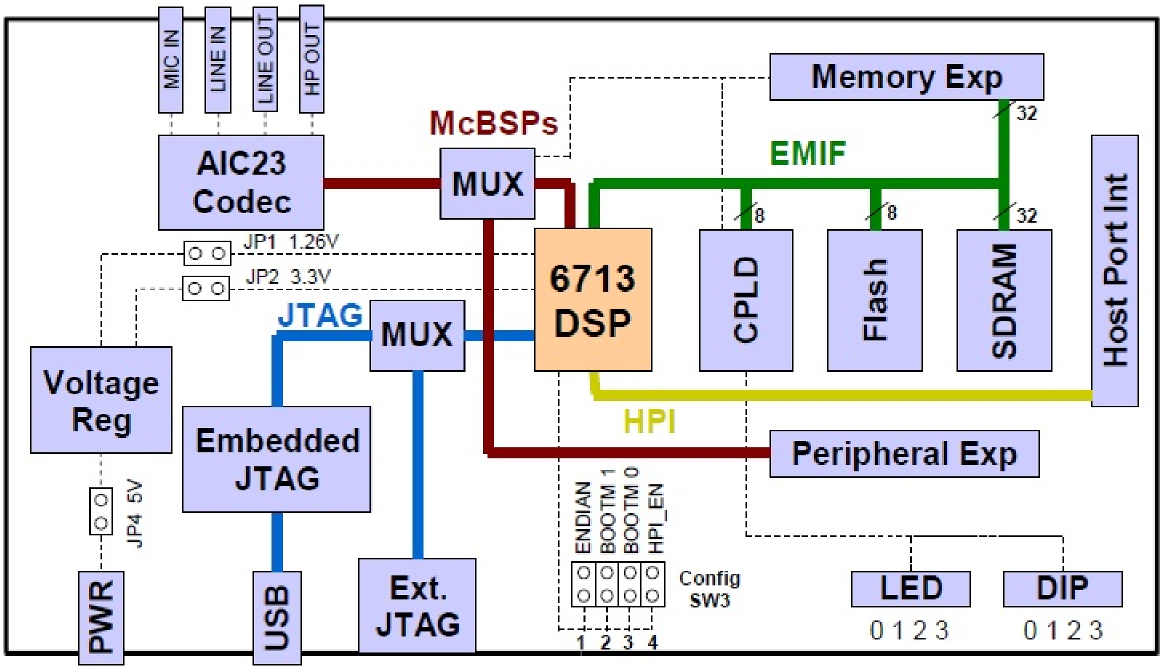

Figure 3. Block diagram for Starter Kit TMS320C671. Taken from [17].

5.3. Discrete components with digital processing

Another option to work with DSPs, overcoming the problems described of working with Starter Kits, is to set up our system with components that are most suited to our problem, that is, mainly, the use of DACs with a higher sampling frequency, such as the AD7892 (Analog, $ 23) which has 18bits of resolution and the ability to get up $1MSPS$, which theoretically would allow the system to work up to a frequency of $500kHz$. Another advantage is that you get a system more adapted to the problem at a lower cost than using a Starter Kit. One problem with this solution is the difficult to achieve a truly compatible and harmonious system, since in these types of components details such as clock speed, type of communication, supply voltages, etc. are essential for the assembled system to work properly. Another problem, not least, is the construction of the system board, since most of the components are surface mounting, and components such as DSP, memory and ADC have many contacts, it makes very difficult to assembly the components using a normal solder. Table 4 again refers to the component costs, taking into account the same considreraciones made above, the cost of this option is similar to the first.

Table 5 compares the adventages and disadvantages of the three methods discussed.

6. Proposed design

The proposed design for IMPETOM tries to improves the previous designs, overcoming the most notable problems by digitalizing the signals in early stages of the process. By doing this we can take advantage of the precision of the digital filtering and demodulation. Also, we don't have the tools needed to build a complicated board with many surface mounting components, then, our desing is based on an Evaluation Board.

The selected board is the OMAP-L137/TMS320C6747 Floating Point Starter Kit ($ 415, Spectrum Digital). The most important caracteristics for us:

- OMAP-L137 processor, with a with a C6747 VLIW DSP floating point processor and an

Table 4. Cost of integrated and discrete components EIT Hardware.

Block	Design	Component	Quantity	Price, each, U$S
Signal Generator	DDS	AD9832	1	11
	Multiplier DAC	DAC8811	2	13
VCCS	Operational Amps.	OPA602	2	10
Current Measurement	Digital potentiometer	AD7376	1	8
Multiplexers	Multiplexer	ADG406	4	12
Amps., filtering	Operational Amps.	INA114	4	12
	Programmable gain amps.	PGA203	2	17
Synch. Demod.	DSP	TMS320C6713B	1	45
Control	DSP	TMS320C6713B	1	0
	Memory	M48Z129V	1	27
	ADC	AD7892	2	23
			Total	**313**

Notes: DDS: Direct Digital Synthesis, DAC: Digital to analog converter, VCCS: Voltage controlled current source, DSP: Digital signal processor, ADC: Analog to digital converter.

Table 5. Advantages and disadvantages of the options discussed

Option	Advantages	Disadvantages
Discrete Components without DSP	Cost	Electrical noise Components imperfections
Evaluation Board	Complete System	No flexibility for components
	Optimal Selection of components	Cost
Discrete components with DSP	System adapted to our system	Difficult that the whole system works in an harmonious way
	Cost less than a Starter Kit	Difficult build process

Notes: DSP: Digital signal processor.

ARM926EJ-S processor operating up to 300 Mhz.

- 64 Megabytes SDRAM.
- USB2 2.0 Full speed interface.
- TLV320AIC3106 Stereo Codec
- Expansion connectors for daughter card use.

The general design is simlar to the one described in 5.2. The codec has 4 input channels, considering that a channel will be used to measure the injected current, there would be three input channels to measure voltage in parallel, so at first it seems more reasonable to start with a single measurement channel and then see if expansion is needed.

This system is intended to perform two significant changes from the previous IMPETOM systems implemented [2, 4], first, measuring the current that is injected. The current source is one of the most important sources of errors in the system [6], due to imperfections in the components such as parasitic capacitances, leading to output impedance which are far from infinite. Therefore, considering that the current value does not vary with load on the reconstruction method is an important source of error, to avoid this we can measure the current that is injected and use the correct value in the reconstruction. For this measurement it is best to use a digital potentiometer, which is controlled by the control block which ensures that the signal obtained makes the most of the range of the ADC.

The other change is in principle to make a single measurement channel and to use a multiplexer to obtain all the necessary measures. This change has the disadvantages of increasing the acquisition time relative to the use of channels in parallel, in addition that the multiplexers are sources of noise and errors [6]. The reason for this change is the complexity and cost of building 16 measuring channels, plus it must have a system capable of handling these signals in parallel, the option used in the IMPETOM project [4], is that of a DAQ, which raises the cost.

7. Conclusions

The systems developed in recent years largely share some methods, such as DDS to generate the sinusoidal signal or a configuration of simple or modified Howland as current source. In the measurement stage, the instrumentation amplifier is followed by an analog to digital converter of at least 16 bit resolution, then, in the digital domain the filtering, synchronous demodulation and other data processing is performed. For control and data processing the DSP is the most popular option for its speed and calculation capacity. In addition, the fewer multiplexers are used, the better the performance of the system. This setting seems to give the best compromise between performance and cost.

The solution implemented in IMPETOM [2, 4], because the technology at the time it was originally developed, is far from what is thought to be the best implementation today. Research continues on several aspects of this development for a prototype according to the set objectives. The availability of a low-cost, noninvasive, without ionizing radiation, which has at all times the evolution of water content in lung space is an aspiration of the intensivists from around the world.

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