PROPOSAL FOR A REAL-TIME MULTI-FRECUENCY IMPEDANCE TOMOGRAPHY SYSTEM

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Abstract: The Electrical Impedance Tomography (EIT) is a technique for obtaining the distribution of the electrical conductivity of a body or medium, useful for tissue and body organs characterization. This paper proposes a portable, low cost, scalable, minimally invasive, novel hardware design of a 16-channel multi-frequency EIT system based on a microcontroller, high speed ADCs, and a FPGA. This design does not intend to follow other designs that utilize 64-channels with emphasis on high resolution imaging or 3D imaging. Instead it focused on real-time imaging for tissue and organ behavior analysis. A prototype setup already implemented includes the front end, an injection/acquisition channel pair and the software for hardware control, data acquisition, and computer link. Through the use of modern FPGAs, it should be possible to provide faster data processing and image reconstruction, therefore revealing abnormalities in the behavior of internal organs. This device also presents itself as a low cost alternative that can contribute to the Venezuelan and Latin America medical institutes, instead of relying on high cost apparatus that are hard to purchase in some major cities and most rural areas.

Introduction

The Electrical Impedance Tomography (EIT) is a technique for obtaining the distribution of the electrical conductivity (real or complex) of a body or medium. The conductivity information is obtained from voltage and/or current measurements from the periphery of the studied region, as a result of the injection of voltages or currents externally applied, of specific amplitude and frequency, through electrodes adhered to the surface of the body. The final objective is to obtain images of the distribution of conductivity by means of mathematical algorithms applied on the retrieved data.

The different tissues of the human body exhibit a great variety of conductivities, and this is why EIT has great potential for obtaining images related to organs behavior and physiological processes. It is known, for example, that the conductivity of the blood changes with the variation of its flow; and air, blood or another liquid in an organ can also affect its conductivity. The presence and variation of all these parameters would be detected in images obtained by EIT. In the case of the cancer, tumors present different electric characteristics from those of normal tissues; with EIT, their presence and location can therefore be studied. If the process of injection, acquisition and collection is carried out repeatedly, a cycle of images is obtained in real time, associated with the behavior of the object or organ under study. Its is to be mentioned that the result of an EIT procedure is a functional image, in contrast with the anatomical images obtained through traditional techniques, such as radiology or magnetic resonance.

Tissue responds differently as the frequency of the applied current is varied. This behavior can contribute to tissue characterization, and has prompted the design of multi-frequency current injection devices. In parallel, a number of image reconstruction techniques, based on frequency variation tissue response, has also been developed. This method is called Multi-frequency Electrical Impedance Tomography (MEIT).

One of the most relevant advantages of employing EIT and MEIT is that data can be acquired in real time, providing a cycle of images that show the organ's behavior. A small size, portable, low cost MEIT device has the potential of becoming a particularly useful diagnostic-screening tool; especially for cases in which other techniques exhibit limitations (for example, X-rays on infants). EIT can also be used to study unilateral lung behavior, i.e., each lung separately, which is not feasible with other traditional techniques as spirometry (measure of flow and volume of air that enters and leaves both lungs) or gammagraphy (technique in which radioactive material is either inhaled or injected, in order to measure respiration and circulation in all regions of the lungs).

This paper proposes a portable, low cost, scalable, minimally invasive, novel hardware design of a 16-channel multi-frequency EIT (MEIT) system based on a microcontroller, a high speed ADC, and a FPGA. The target of this design differs from those that utilize 64-channels and emphasize on high resolution or 3D imaging; instead it seeks real-time imaging for tissue an organ behavior analysis.

ISSN: 1727-1983

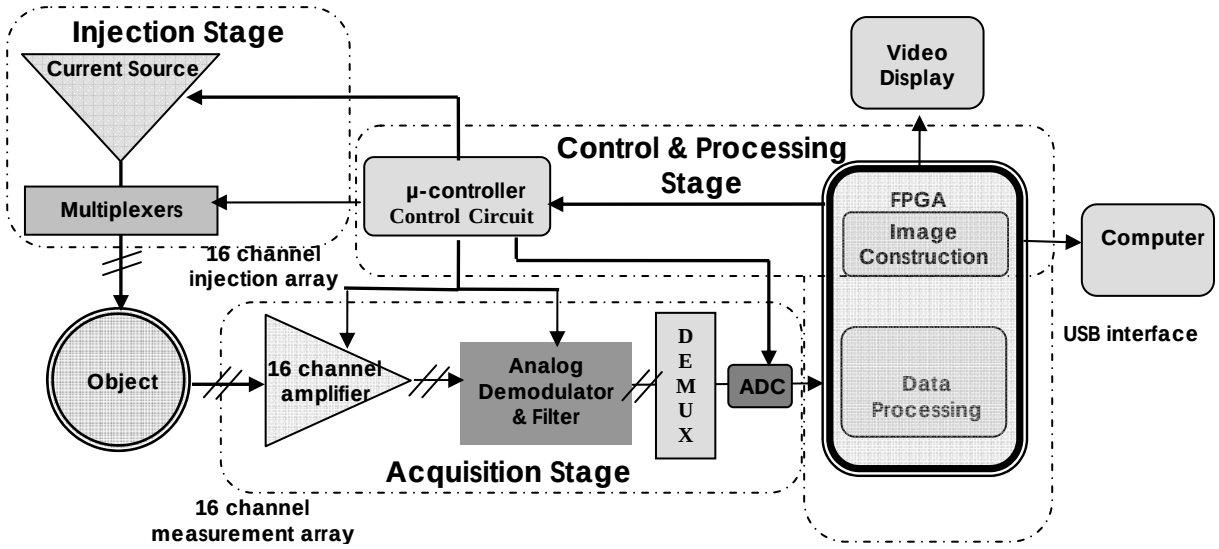

Figure 1: Block Diagram of MEIT proposed design

Methodology

The design presented in this study uses a 16-electrode array, for both impedance measurements and current injection. An electrical current of 2mA, with a frequency range spanning from 35 KHz to 194 KHz, is injected through an electrode pair, and the resultant potential differences measured at the remaining adjacent electrode pairs are demodulated and transmitted to a high-speed analog-to-digital converter, and sent afterwards to the FPGA. Initially, the image reconstruction process was performed off-line, using software developed by the Electrical Impedance and Diffuse Optical Tomography Reconstruction Software (EIDORS) group, at the Kuopio University in Finland, based on the Gauss-Newton algorithm [26]. The block diagram of the system, as depicted in Fig. 1, comprises an injection, acquisition, control and processing stages.

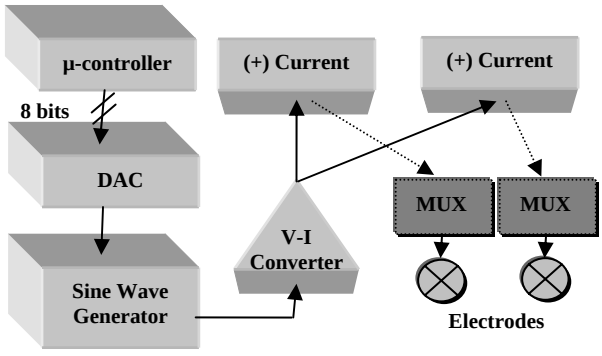

Figure 2: Block Diagram of Injection Stage

The injection stage (see Fig. 2) employs a sine function generator chip, with a central frequency set at 115 KHz, for a 35-194 KHz frequency range in 2 KHz-steps; and a voltage-to-current converter, that uses a built-in buffered current mirror. Two current channels are generated, for both current sourcing and sinking. In addition, two analog multiplexers are placed between the current channels and the electrodes, to provide support for any injection scheme proposed by earlier works [1, 6, 8, 10]. This means that current could be injected, using any of the known electrode pair sequences (adjacent, polar, etc).

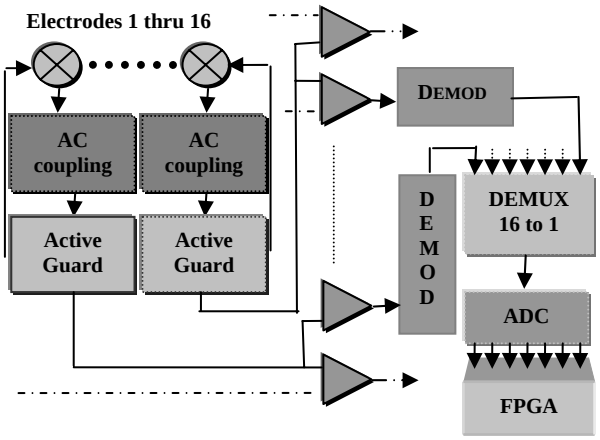

Figure 3: Block Diagram of Acquisition Stage

The acquisition stage (see Fig. 3) consists of the measuring electrodes, a high-pass filter for AC-coupling, and active guard circuits, which contribute to reduce the interference caused by common-mode input. It also incorporates a demodulator, de-multiplexer and an analog-to-digital converter. The voltages measured at the electrodes enter a synchronous demodulation stage, which has a multiplier and a low-pass 5th order Bessel filter. The demodulated signal now enters an analog-to-digital stage, which utilizes a 16-bit ADC with 1.25MHz sampling rate. It also includes a 16-bit Successive Approximation Register type converter, which enhances high performance and low power consumption. It is worth mentioning that the system uses a semi-parallel acquisition scheme, in order to

ISSN: 1727-1983

reduce the skew introduced by the different blocks of the system. Regardless the injection scheme, the system uses a fixed adjacent acquisition array, since the use of a different electrode pair acquisition sequence does not affect the image obtained significantly. This means that the spatial resolution does not improve significantly by changing the sequence or adding more electrodes to the same thoracic array.

The control & processing stage are based on a microcontroller and a FPGA-based processing unit (see Fig. 1). The microcontroller handles the injection stage, therefore providing a user selectable scheme (the sequence of current injection), and provides control for the acquisition stage, by managing the conditioning circuitry, the de-multiplexers and the ADC. The output of the ADC is passed to the processing unit, based on a FPGA, so that it can be processed and converted into a video signal. The microcontroller selection, from the Motorola family, was based in its low cost and high availability, with: 8 bit bus, 8 MHz internal frequency, serial communication interface, internal PLL, and sufficient I/O ports.

The processing stage is based on a FPGA board, capable of controlling tasks ranging from digital parallel data acquisition, filtering algorithms execution, image reconstruction, to real time video output generation. The main advantage gained by using FPGA technology is the inherent capacity for parallelism.

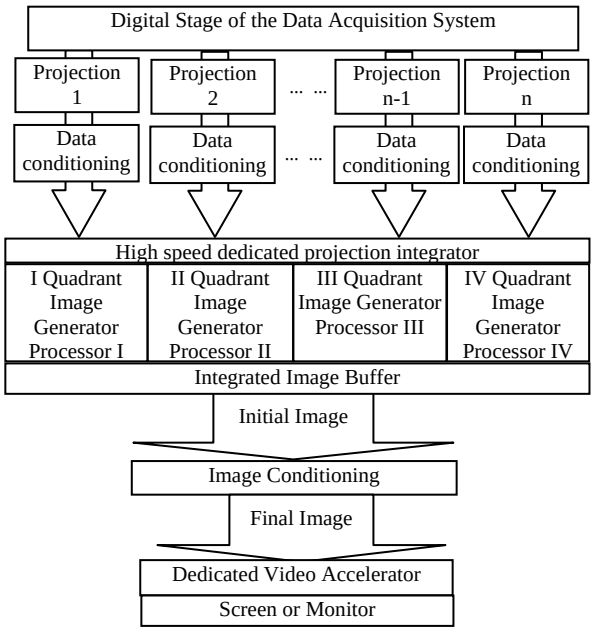

Figure 4: Block Diagram of Image Reconstruction

The FPGA processing system being development is based on a parallel processors architecture. Experiments with the FPGA Xilinx Spartan3 XCS3S1000 platforms, interconnected by a parallel bus running up to 500 Mbps [23]. This setup can therefore support an ample variety of parallel and hierarchical applications. The platform was tested by processing and generating low resolution images (64x64 pixels), reconstructed using a back-projection algorithm. The input data was collected from predefined phantoms [23]. There exist a number methods that use parallelism in back-projection algorithms for tomography; Fig. 4 illustrates a simple version.

In ideal conditions, the architecture can be formed by in-line blocks constituted by combinational circuits and/or function specific finite state machines; where the speed of the acquisition stage, which feeds the projection buffers, is a determinant factor of the image re-construction speed. The processor that executes the algorithm of back-projection is in reality 4 image generators that divided the work in order to calculate the values for the pixels in quadrants or zones of the image. When the number of projections is high (and it usually is), the parallelism in the conditioning of initial data can be adapted to process groups of projections and not individual projections, of course it depends on the internal capacity of the integrated circuits utilized.

Discussion

The control of the injection and acquisition stages by means of a microcontroller was inherited from previous designs [11]. Although only a single electrode channel was actually constructed for the previous prototype, the control circuitry and software for the 16-channel expansion was completely implemented. Impedance load variation at a fix frequency produced an error less than 1% in current flow amplitude. The same experiment was performed through the entire frequency range of the MEIT system using 10 KHz steps, and as a result, an error less than 1% in current flow amplitude was obtained. The system prototype exhibited a signal to noise ratio (SNR) over 88dB, complying with the optimal range for this type of equipment, which was measured using the method employed by Smith [25]. On the other hand, the common mode rejection ratio (CMRR) was below 60dB, which fulfils the minimum desired CMRR for MEIT systems [6]. In order to calibrate the equipment and to verify the precision of its measurements, simulated values for one selected injection/acquisition pair were introduced in a matrix included with the EIDORS package, and then compared to the originally included data set. This matrix corresponds to a real cross-sectional image of the thorax. It should be mentioned that the future designs should no longer require the microcontroller and have the FPGA manage all stages. The algorithms and architectures for image generation are currently being improved. In order to optimize the FPGA based processing unit.

Conclusion

A real-time, low cost, minimally invasive, configurable, MEIT prototype system was proposed, that provides a friendly user interface, which is scalable, and is adaptable to change. Current testing shows promising results that encourages further development and optimization of the design.

ISSN: 1727-1983

The proposed design was conceived for real-time MEIT applications; however, proper adaptations and expansions have been considered for resolution enhancement and 3D capabilities, considering minimal or no central hardware changes. A complete functional prototype of the system is expected promptly, based on the block diagram presented in this work.

References

[1] ARPINAR, E. Y B. EYUBOGLU (2001) 'Microcontroller controlled, multi-frequency electrical impedance tomography', Proceedings of the IEEE/EMBS 23rd Annual Conference, Turkey, 2001.

[2] BERTEMES-FILHO P., B. BROWN Y A. WILSON (2000), 'A comparison of modified Howland circuits as current generators with current mirror type circuits', Physiological Measurement, Vol. 21, pp. 1-6, 2000.

[3] BLAD B., LINDSTRÖM K., BERTENSTAM L., PERSSON B. Y N. HOLMER (1994_, 'A current injecting device for electrical impedance tomography', Physiological Measurement, Vol. 15, Supp. 2A, pp. 69-77, 1994.

[4] BOURNE, J. (1996), 'Biomedical Engineering', Begell House, Inc. New York, USA, 1996.

[5] BRAGÓS R., ROSELL J. Y P. RIU (1994), 'A wideband AC-coupled current source for electrical impedance tomography', Physiological Measurement, Vol.15, Supp. 2A, pp. 91-99, 1994

[6] CASAS, J (1998), 'Contribución a la obtención de imágenes paramétricas en tomografía de impedancia eléctrica para la caracterización de tejido biológicos', Doctoral Thesis, Universidad Politécnica de Cataluña, Spain, 1998.

[7] Datasheet de Texas Instruments ADC ADS8401

[8] DENYER C., LIDGEY F. ZHU Q. Y C. MCLEOD (1994), 'A high output impedance source', Physiological Measurement, Vol. 15, Supp. 2A, pp. 79-82, 1994

[9] DENYER, C. (1996), 'Electronics for real-time and three-dimensional electrical impedance tomography', Doctoral Thesis, Oxford Brookes University, England, 1996.

[10] FRERICHS, I. (1996), 'Electrical impedance tomography (EIT) in applications related to lung and ventilation: a review of experimental and clinical activities', Physiological Measurement, Vol. 21, pp. R1-R21, 2001.

[11] GRAVIS K., FARKAS E. (2004) 'Diseño e Implementación de un Sistema de Tomografía por Impedancia Eléctrica', Thesis, Simón Bolívar University, Sartenejas, Venezuela

[12] HAYKIN, S. (2001), 'Communication Systems', John Wiley and Sons Inc., New York, USA, pp.95 – 98, 2001.

[13] HUHTA, J. Y J. WEBSTER (1997), '60-Hz Interference in Electrocardiography'. IEEE Transactions on Biomedical Engineering. Vol. 20, No. 2, Marzo 1973

[14] JUSTINIANO, R. Y W. CORONADO (1997), 'Sistema de adquisición de señales cardio-respiratorias para pruebas autonómicas', Thesis, Simón Bolívar University, Sartenejas, Venezuela, 1997.

[15] LIEDTKE, R. (1997), 'Principles of Bioelectrical Impedance Analysis', http://www.rjlsystems.com, 1997.

[16] MALMIVUO J. Y R. PLONSEY (1995), 'Bio-electromagnetism', Oxford University Press, New York, USA, 1995.

[17] MEESON S. (1997), 'An investigation of optimal performance criteria in Electrical Impedance Tomography', Doctoral Thesis, Universidad de Southampton, England, 1997.

[18] METHERALL, P. (1998), 'Three Dimensional Electrical Impedance Tomography of the Human Thorax', Doctoral Thesis, Universidad de Sheffield, England. 1998.

[19] METTING VAN RIJN A., PEPER A. Y C. GRIMBERGEN (1990), 'High quality recording of bioelectric events. Part1; Interference reduction, theory and practice', Medical and Biological Engineering and Computing, No 28, pp. 389-397, 1990.

[20] MUELLER J., SILTANEN S., Y D. ISAACSON (2002), 'A direct reconstruction Algorithm for Electrical Impedance Tomography', IEEE Transactions in Medical Imaging, Vol. 21, Num. 6, pp.555-559, 2002.

[21] PALLÁS-ARENY, R. (1988) 'Interference–rejection characteristics of bio-potential amplifiers: A comparative analysis'. IEEE Transactions on Biomedical Engineering. Vol. 33, Num. 11, 1988

[22] SEDRA, A. Y K. SMITH (1998), 'Microelectronic Circuits', Oxford University Press, New York, USA, 1998.

[23] SIERRA R., DE CASTRO O., SALAZAR A. (2005) 'Plataformas de procesamiento jerárquico y paralelo con FPGA para aplicaciones de tiempo real', unpublished, 2005.

[24] SMALLWOOD, R., HAMPSHIRE A., BROWN B., PRIMHAK R., MARVEN S. AND P. NOPP (1999), 'A comparison of neonatal and adult lung impedances derived form EIT images', Physiological Measurement, Vol. 20, pp. 401-413, 1999.

[25] SMITH, R., FREESTON I. Y B. BROWN (1995), 'A real-time electrical impedance tomography system for clinical use – design and preliminary results', IEEE Transactions on Biomedical Engineering, Vol. 42, Num. 2, pp. 133-140, 1995.

[26] SMITH, R.M. (1991), 'AC Coupling Instrumentation and Difference Amplifiers', Burr-Brown Application Bulletin, USA, 1991.

[27] THAKOR, N. Y J. WEBSTER (1980) 'Ground–free ECG recording with two electrodes', IEEE Transactions on Biomedical Engineering, Vol. BME-27, No. 12, 1980.

[28] VAUHKONEN, M., LIONHEART W., HEIKKINEN L., VAUHKONEN P. Y J. KAIPIO, 'A MATLAB package for the EIDORS project to reconstruct

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two-dimensional EIT images', Physiological Measurement, Vol. 22, pp. 107-111, 2001

[29] VAUHKONEN, M. (1997), 'Electrical Impedance Tomography and prior information', Doctoral Thesis, Universidad de Kuopio, Finland. 1997.

[30] WEBSTER, J. (1998), 'Medical Instrumentation: Application and Design', Houghton Mifflin Company, Boston, USA, 1998.

[31] WINTER, B. (1983), 'Reduction of Interference due to common mode voltage in Biopotential amplifiers. IEEE Transactions on Biomedical Engineering. Vol. 30, No. 1, March 1983.

[32] ZHU, Q., MCLEOD C., DENYER C., LIDGEY F. Y W. LIONHEART (1994), 'Development of a real-time adaptive current tomography', Physiological Measurement, Vol. 15, Supp. 2A, pp. 37-44, 199

ISSN: 1727-1983