HARDWARE DESIGN AND RECONSTRUCTION RESULTS OF SUT-1 EIT SYSTEM

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ABSTRACT

We describe a newly developed 2-D system for EIT SUT-1, which works efficiently in different types of applications. The system consists of a PC computer in which an I/O card is installed with an external current generator, a multiplexer, a power supply and a phantom with an array of normal ECG electrodes. The measurement system provides 12-bit accuracy and hence, suitable data acquisition software is prepared accordingly. The synchronous phase detection method was implemented for the voltage measurement. Different methods of image reconstruction are discussed in this paper. The results of simulation and real measurement of the system are presented. Reconstruction programs were tested using MATLAB environment. The system was tested with both 32 electrodes (static mode) and 16 electrodes (difference imaging, APT mode) in a 2-D Domain. Better results have been produced in APT mode of operation. A considerable reduction in diagnostic costs can be achieved using this system.

INTRODUCTION

The electrical properties of different matters have been the main topic of many investigations for many years [1], [2]. In Electrical Impedance Tomography (EIT), the differences in the electrical properties, i.e., conductivity distribution inside the object is used to generate a tomographic image [2], [3]. EIT is capable of handling both medicine and industrial applications [4], [5]. The advantage of such a technique over other imaging modalities is that it provides a non-invasive ("non-destructive" in an industrial terminology) method and requires no ionizing radiation. Furthermore, EIT is a relatively low cost and simple functional technique. Moreover, a portable measurement system could also be designed for it. The most important drawback of EIT is its poor image resolution, which is often restricted by the number of electrodes used for data acquisition. The problem of electrode positioning error is also an essential problem in EIT [5], [6]. Data acquisition is typically done by applying an electrical current to the object using a set of electrodes and measuring the developed voltage between other electrodes [2]. Different aspects of EIT have been studied earlier [7].

Fig. 1. illustrates a general view of an EIT system. Generally 2-D the EIT systems could be categorized into two different sets namely: ACT (Adaptive Current Tomography) and APT (Applied Potential Tomography).

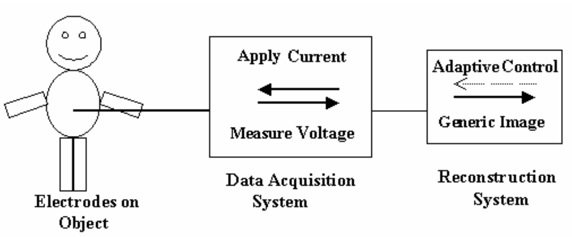

Fig. 1. General View of an EIT System.

MATERIALS AND METHODS

Mathematical Formulations

From a mathematical point of view, it has been shown that the governing equations for EIT image reconstruction, derived from Maxwell's Equations, [5] are:

$$\nabla.\left[\tilde{\sigma}(P).\nabla\tilde{U}(P)\right] = 0 \quad \text{at B (B is the object)} \quad (1)$$

$$\tilde{\sigma}(P)\frac{\partial\tilde{U}(P)}{\partial\upsilon} = J \qquad P \in S \quad \text{(Surface)} \quad (2)$$

$$\int_S \tilde{U}(P)ds = 0 \qquad P \in S \quad (3)$$

where P is a point inside of the object B and J is the electric current in excitation electrode, $\tilde{U}(P)$ is the voltage (complex number) and $\tilde{\sigma}(P)$ is the complex admittance of B in which:

$$\tilde{\sigma}(P) = \sigma(P) + j\omega\varepsilon(P) \qquad (4)$$

for angular frequency of ω and electrical conductivity of σ and permittivity of ε.

Fig. 2. shows two possible impedance models of the human tissue [2]. These models are used in discretized model of the forward problem. The impedance changes with the frequency because of capacitive effect of the cell membranes as well as the change in electrical conductivity by frequency [2].

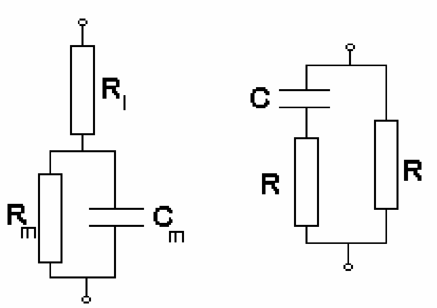

Fig. 2. Impedance models for human tissue.

In order to map the resistivity inside the body properly, we have designed and fabricated a PC-based EIT system at Sharif University of Technology, Tehran, Iran. The system is able to reconstruct the images in 2-D domain. We have tested the system using both 16-electode and 32-electrode modes of operation with different reconstruction algorithms.

Hardware

Fig. 3. shows a simple block diagram of an electrical impedance measurement system. This is a four electrode impedance measurement technique includes a current source for the excitation and differential amplifier for the voltage measurement.

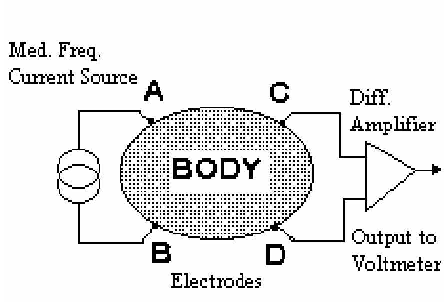

Fig. 3. Impedance measurement.

A block diagram of a complete EIT system is shown in Fig. 4., where the main blocks of system hardware are presented. For each measurement channel, a well-known block described in [3] is used. The computer is a usual Pentium PC, which is connected to the measurement system through an Input Output interface (I/O) card. In the main board, a current generator with 5 mA @ 23 KHz and a precise voltage measurement (using synchronized pulse demodulation technique) are implemented. The accuracy of digital system is 12 bits. It is shown that the 12 bit digital resolution is a reasonable choice for most EIT applications [2]. The switching between different pairs of electrodes is carried out by the computer using a multiplexer card (MUX board). The collected data from all possible voltage measurements are fed to image reconstruction software. In the following, a brief description of individual modules of this system is presented.

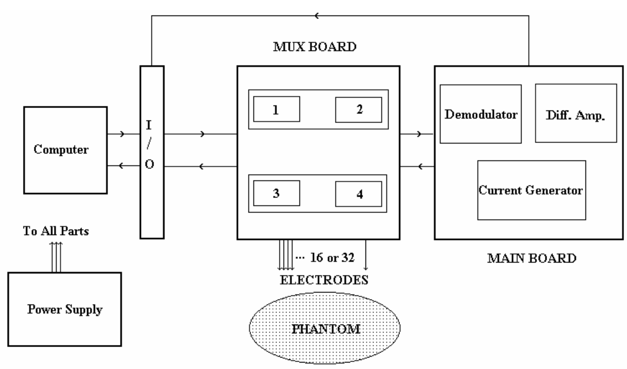

Fig. 4. Block diagram of an EIT system.

I/O card: For the I/O module, an ADVANTECH PCL-812PG I/O card is used. It consists of 16 bit programmable I/O card with 12-bit successive approximation analogue to digital converter, (30 kHz sampling rate), programmable Time/Counter/Gain and two 12 bit monolithic multiplying digital to analogue converter output channels. Due to application of an unsophisticated analogue to digital conversion algorithm, it is not a fast sampling card. To overcome this shortcoming, it is planned to use a faster card in the new version of the system.

Current Generator: In this module, we use a fixed frequency current injector. For an EIT current generator, the highest attention has to be paid to the amplitude stability due to its high influence on the total system error. Different circuits were built and tested, and finally we ended up with a digital generation method by means of an EPROM (27C258). Furthermore, the EPROM was programmed to produce 256 steps of a 23 KHz sinusoidal waveform. An 8-bit counter was used for reading the EPROM data, and then data were applied to a digital to analogue converter (DAC-0808). The system internal clock ran at 6 MHz. One of the most important advantages of this circuit is related to the synchronous pulses for demodulation, which can be obtained by the address line decoding. Zero crossing point and amplitude peak point can also be determined. The total harmonic distortion (THD) of this current generator is determined to be about 1.3%. The output of the digital oscillator is fed in to the current source through a normal gained buffer stage (LF-357). Our voltage control current source (VCCS) is a buffered current mirror circuit. We use Analog Devices AD644 as the main part and some LF-411 and LF-412 for buffering. The output current is around 5 mA.

Voltage Measurement: Another important part of the system hardware is the voltmeter. We used a synchronous differential demodulator. This method is a common method for demodulation in EIT. The noise cancellation capability is one of the important features of this circuit. The circuit is a "Sample and Hold" type of demodulator. An AD-625 instrumentation amplifier is used as the "heart" of the measurement system. Output signal of the demodulator is fed into an I/O card by a controlled gain buffer amplifier block, which uses CA-3130 at the final stage. In APT mode of operation, the offset and gain error of this stage is of less importance, so, for a better Signal to Noise Ratio (SNR), the gain could be increased to a maximum reasonable value. The time duration in which the voltage measurement is performed, is an essential parameter in the system overall speed. This time also depends on the multiplexing switching time between different channels. In order to increase the data reading time, it is possible to use fast analogue to digital converters, separate demodulator for each channel, and/or decrease in multiplexing time by means of faster digital switches. For example, in APT mode, 16 electrodes can be directly connected to our 16-bit I/O card for voltage measurement to save the multiplexing time and reduce the error.

We have examined different methods namely cross and opposite for data acquisition and their effects on distinguishability of objects. An example of such methods is shown in Fig. 5. where the variation of measured voltages vs. voltage no. for a current injector is illustrated. The level of detected signals is lower in adjacent current pattern but the dynamical range of the detected voltages is higher in opposite electrode pattern. For further details in different current pattern see for example [2].

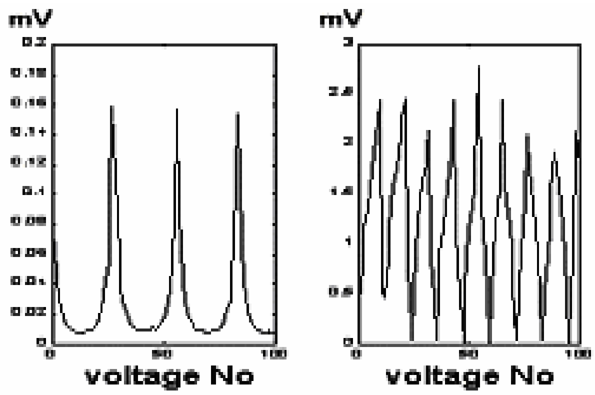

Fig. 5. Measured voltages vs. Voltage No, for the Adjacent (left) and Opposite (right) arrangements

Multiplexer: In order to perform data acquisition in 32-electrodes and 16-electrodes mode, a multiplexer circuit is necessary for switching current injector and voltmeter among the different data channels. Our multiplexer circuit (MUX) consists of four 32x1 analogue multiplexers. Each multiplexer is a combination of two 16x1 IC-4067 multiplexers. The most significant type of errors arising from the MUX board, labeled as r_{on}, is related to the semiconductor switches, and also cross-talk between different channels. It has to be noted that the r_{on} does not have a constant value, but different values for different channels. It is a function of different parameters like temperature and current in each channel. It is desirable to have the value of r_{on} as small as possible.

Electrodes and Phantoms: Different cylindrical phantoms are imaged with this device. In order to simulate human tissues behavior, saline solutions with different concentrations are used. Normal ECG electrodes, i.e., Ag-AgCl type, are served as an electrical contacting media. Cu electrodes could be another choice for a better and more realistic simulation of electrode-skin contact impedance.

Software

According to the predefined tasks set by the system hardware design, different programs were developed. For data acquisition, the software (system control software) is developed using C++ environment. This software controls the entire imaging process. For image reconstruction, the software is developed using MATLAB. Moreover, a simple program is developed to generate different meshes for Finite Element Modeling (FEM). In this model, triangular elements are used for image reconstruction (see Fig. 6.). Then, for the image reconstruction in the 32-electrode mode of operation, a modified Newton-Raphson method is implemented.

During APT mode of operation, image reconstruction is performed with 16 electrodes using Back Projection algorithm and iso-potential lines. Basically this is the "Sheffield Algorithm" with some changes and modifications corresponding to the system specification.

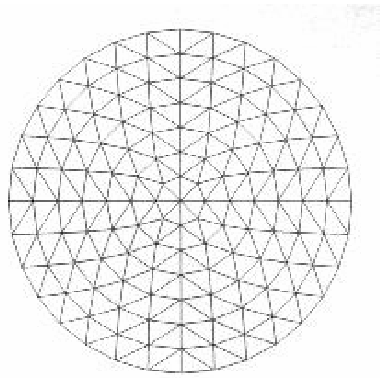

Fig. 6. Mesh for the forward problem of EIT.

RESULTS

The system's performance was tested using simulations and real measurement. Here, we review examples of our experimental results.

Simulation Results

As described before, EIT is very sensitive to different errors. Using simulations, we tested our reconstruction software under different normal conditions and got satisfactory results. However, abnormal conditions are more important for evaluating the system overall performance. One of the interesting issues was to see what would happen if the positions of electrodes changed. To do this, a homogeneous medium is used and just one element with different resistivity was implemented at the right side of the second sector. Then 1^{mm} error was introduced in the exact position of the electrode No. 1. The simulated data was supplied to the reconstruction algorithm. The result obtained from the reconstructed image under this condition is shown in Fig. 7. A big error is introduced specially in the adjacent elements as shown on Fig. 7. The basic element is seen black (it has to be white) and this error was propagated through the image. This simulation shows that the mis-positioning of electrodes is one of the important factors impacting the image artifacts.

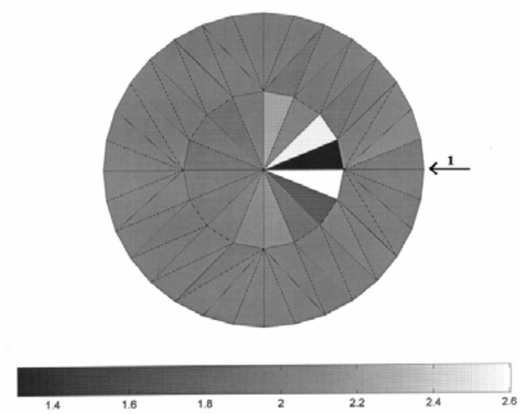

Fig. 7. Reconstructed image showing electrode positioning error

Fig. 8. shows the reconstruction results from the regularized Newton-Raphson method using simulation data for one and two inclusions.

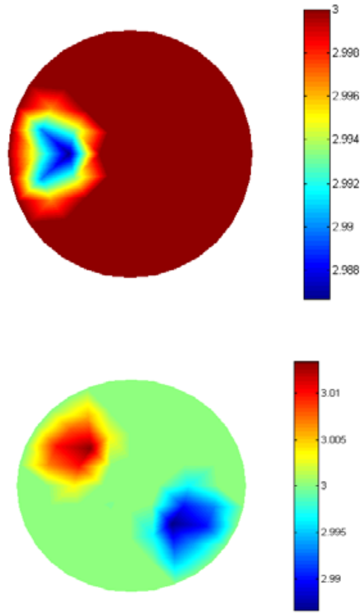

Fig. 8. Simulated test reconstructions using regularized Newton-Raphson method.

Real Measurements Results

For this part, we measured the voltage and then reconstructed images in 16 and 32 electrodes modes. In practical conditions, EIT is very sensitive to noise. Electrodes are connected via a shielded cable to the system for noise reduction. Figures 9-10 illustrate two actual images using a simple phantom in the APT mode. The phantom was made of PVC cylinder with 30 cm diameter and filled with saline. Fig. 9. shows the design and experimental results for a phantom where an object with different resistivity (a normal milk bottle) is put at the corner, i.e., at x=0 cm and y=-6 cm from the geometrical center of the tank.

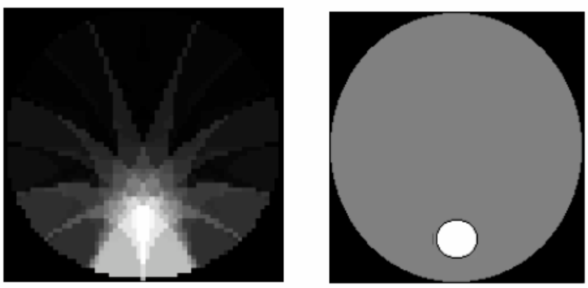

Fig. 9. A real test object and its EIT reconstructed image using back projection method.

Fig. 10. shows the design and experimental results for a phantom with two objects. Measured data were transferred to the computer, the reconstruction algorithm applied and image was obtained using back projection method. As seen in Figure 9, a star artifact is resulted from back projection. This is a well-known artifact for the back projection method. Basically, it is due to limitation in the number of projections. If the projections number (ray-sum) is increased, the size of this artifact will decrease.

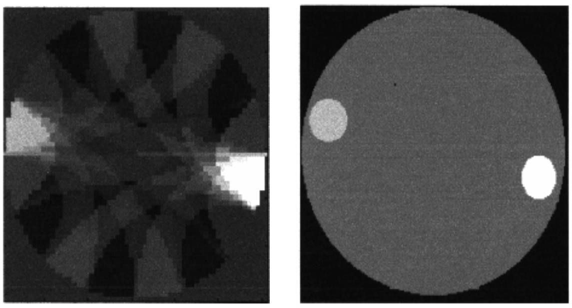

Fig. 10. Another real test object and its EIT reconstructed image using back projection method.

DISCUSSION

The results presented in this paper are in 2-D EIT system. Its accuracy and functionality are tested for different conditions. The system can be used for 3D applications, simply by changing the electrode arrangement and employing 3D reconstruction software. We are working in further advancement of 3D EIT software. The system is designed such that it can be upgraded to function as a multi-current generator adaptive system. Also, by modification of the sampling circuit, the system will be able to detect the imaginary part of the signal and accordingly the phase of the signal can be detected. For this purpose, the voltage sampling has to be carried out during zero crossing instead of peak sampling.

The system has been tested under in-vitro condition. In order to perform in-vivo measurement, the IEC-601 safety standards have to be observed. The system needs some changes using isolating components, e.g., use of opto-couplers in the data acquisition circuit can provide a complete electrical isolation. Finally, the system can be also used for different EIT applications such as industrial process control.

Comparing to the best EIT system in the world namely ACT3 [2], the SUT-1 has less functionality. For example in ACT3 one can use adaptive current pattern by using multiple current source, this is not a feature in SUT-1. Multi-frequency EIT systems are going to be built in future, SUT-1 is still a single frequency system. Unfortunately there are not many EIT systems commercially available. Few commercial EIT systems (single channel systems) are very expensive (they cost from $20 K to $50K), an ACT type EIT system if available will be extremely expensive. We designed and fabricated SUT-1 [2] with a maximum cost of $1200. The simplicity and the price of SUT-1 are the major advantages of our system. The functionality of system shows that a simple system can operate in the design basis functions efficiently.

CONCLUSION

The hardware parts of an engineered EIT system are presented. The system currently works in the 2-D mode but can be extended to work in the 3-D mode. This can be done by using better electrodes (e.g., active electrodes), faster data acquisition techniques, and multi-frequency and real time 3-D image processing. Beside potential medical application, using the system to optimize the metallurgical and chemical processes is among its potential industrial applications.

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