Reconstruction of electrical impedance tomography using improved Newton-Raphson algorithm based on wireless distributed system

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Abstract

In the fields such as non-destructive testing and structural health monitoring, Electrical Impedance Tomography (EIT for short) caused concern for people in recent years. This paper introduced the wireless distributed EIT data acquisition system for the advantages of low costing, reliable, accurate and efficient. For this wireless EIT system we have designed the corresponding software which could receive and process data and reconstruct image in one step. On the other hand, based on the existing algorithms this paper proposed the improved Newton-Raphson algorithm to reconstruct image. The experiment result proved that both the system and algorithm was a successful, accurate and optimized for EIT experiment.

Keywords: electrical impedance tomography, wireless sensor network, distributed acquisition system, improved Newton-Raphson algorithm

1 Introduction

With the advent of technology, various kinds of Non Destructive Testing (NDT for short) technologies such as ultrasonic detection, radiographic detection, magnetic testing were significantly developed. Many of them have been widely employed in the areas of architecture, medicine and biology. As the new generation of NDT technology, EIT became one of the significant research tasks in the related field.

EIT was firstly proposed by Swanson D.K. from University of Wisconsin Madison in 1976. In 1983 Brown and Barber from University of Sheffield in England had gotten the internal image of human being's forearm tissue with EIT [1].Soon after that, M.Vauhkonen from Cheju National University had successfully enhanced the resolution of EIT by using the Kalman filter. In 1995 Smith and Brown established the first EIT system for clinical use. To this day, it had been proved by theoretical analyses and experiments that EIT as a newly arisen technology was a valid, efficient and safe way to achieve the non-detection in related fields.

Previously, many colleges and research institutions had already proposed the mature EIT experiment platform. As far back as 1978 Henderson and Webster had made their "Impedance camera" for displaying the image of people's heart and lung. It was the earliest EIT experiment in the world. Afterwards, many researchers had continuously tried various approaches to improve the data acquisition equipment and imaging algorithms. But unfortunately, even to this day there was few researchers had tried to use wireless sensor network (WSN for short) to achieve the data acquisition equipment. Based on the long-term studies, this paper proposed the wireless distributed EIT system consisted of the wireless nodes, wireless gateway, computer and the corresponding software. The kind of system could promote efficiency of EIT experiment significantly. Not only that, the system reduced the noise interference came from the signal acquisition circuit dramatically which yield to the greater accuracy of data [2]. We chose the carbon fiber felt as the object to be measured for its excellent mechanical character and sensitivity of resistivity. And on account of data with greater accuracy, this paper had come up with an improved Newton-Raphson algorithm which was used to reconstruct the image of carbon fiber felt experiment. The corresponding software wrote with LabVIEW could communicate with hardware (specifically refers to the wireless gateway device) by serial protocol and reconstruct the image by calling the MATLAB script [3]. The system and algorithm were experimentally validated.

2 Data acquisition

A complete EIT data acquisition system consisted of electrodes, power source, signal acquisition circuit, and if possible, the data processing software. The electrical signal would be converted to digital data and be used to reconstruct image at last.

Obviously, among the numerous factors, the accuracy of raw data was the most important and direct factor affecting the imaging result. So in order to obtain the more accurate raw data, we needed to get the value of the electrical signal as accurately as possible - this was also the intent of design about each kind of data acquisition system.

2.1 MODELS FOR TRADITIONAL DATA ACQUISITION

Most of the EIT data acquisition system could be classified by series system, parallel system, distributed system and adaptive system [4]. Among them the series system was cumbersome to install and to use. And that the adaptive system was not applied widely for the reason that the algorithms for this system were not mature and reliable.

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Therefore, many of researchers experimented with the parallel system and distributed system.

In the course of experiment, the electrode was distributed uniformity on the surface of the object to be measured. At this point, the electrical signal was injected into the object through the two exciting electrodes. Then, the researchers would collect the output signals from other electrodes to be computing and analysis. This kind of data acquisition system was called parallel system. The parallel system had the advantages such as cheap in cost and high in reliability, which made it widely used in EIT related field. It was more efficient than serial system.

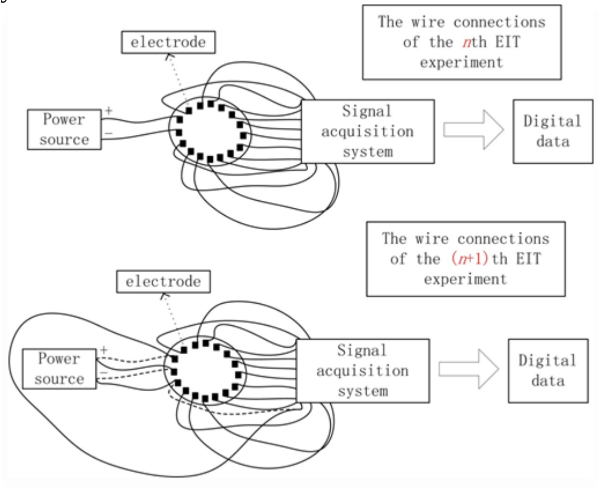


FIGURE 1 the wire connections of the parallel systems

The distributed system was more accurate than the parallel system. Given that the noise interference was mainly generated when signal transferred between the electrodes and data acquisition system, this kind of system usually put the signal conditioning circuits as close to the electrodes as possible. The original signal would to be converted to the digital signal, which was not vulnerable to be disturbed. Then, the anti-interference signal would be sending to the receiving end through shield wire. In this way, the noise interference, which caused in the process of signal transmission could be reduced effectively, but relatively, such system with higher demanded on stability would certainly cause the more expensive hardware cost.

As mentioned earlier, those kinds of traditional data acquisition systems were all limited to wired-transmission, which would bring about the tedious course of EIT experiment. With parallel system, for example, the Figure 1 had showed the wire connections of the traditional systems as a brief explanation. It must be reminded that all figures about the hardware structure of EIT in this paper (specifically refer to Figures 1-4) had omitted most or all of the ground wires to avoid causing visual clutter. Figure 1 showed wire connection of the model for parallel system, and the traditional distributed system was not better than the former. The circuit structural difference between the two kinds of systems was the distributed system equipped with the signal acquisition circuits for each electrode. From Figure 1 we could see that when we finished the nth data acquisition, we should break and reconnect at least 3 wires (excluding the ground wires) before we started our (*n+1*)-th data acquisition. Worse still, if there were quantity of electrodes, we might image that the whole EIT experiment would consume plenty of time even we would connect the circuit incorrectly from carelessness. Indeed, all these complicated work would not be reduced in the traditional distributed.

2.2 MODEL FOR WIRELESS DISTRIBUTED DATA ACQUISITION SYSTEM

As stated above, the expensive costing of traditional distributed system was derived from the complex signal conditioning circuit. And at the same time, this system model also caused the complicated work for installing the equipment. In this case, the technology of wireless sensor network could solve all the problems at a stroke. We might set the wireless device close to the electrode to collect the output signal with a simplified, low-cost and efficient signal conditioning circuit and send the data to the receiving end through electromagnetic – wave [5], by which way we would not focus on the noise interference from the wired transmission circuit.

As the improvement of the traditional system, this paper introduced the wireless distributed data acquisition system. By using the technology of WSN, the system could save lots of filters which were designed to restrain the disturbance-this would also save lots of costing on hardware and even might improve the accuracy of data acquisition. The model for system could be showed as Figure 2.

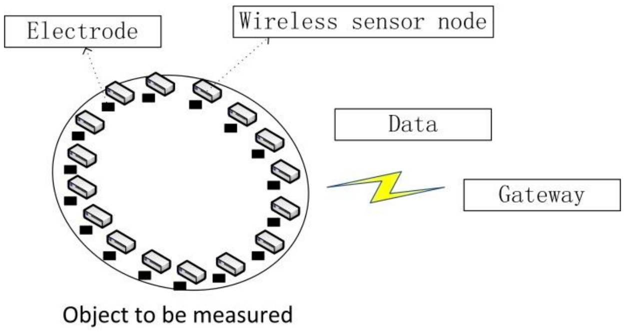


FIGURE 2 model for wireless distributed data acquisition system

With the model showed in Figure 2, all of the nodes could be switched between both output mode (for providing driving current) and input mode (for collect signal) at any time. In addition, each node was equipped individual signal conditioning circuit, which could collect and handle the voltage signal.

Once the EIT experiment started, the node which was chose to be electrical signal provider and the nodes which were chose to be signal collect device would work automatically or manually [6]. When the collecting nodes had collected electrical signal, it would filter the noise at first. Afterwards the processed signal would be converted to digital signal and be sent to the gateway directly by wireless network, which could prevent noise interference from wired transmission absolutely. Compared with the systems mentioned above, the wireless distributed data acquisition system had even no need of making any change on the hardware during the whole EIT experiment.

As the core of the wireless network, the gateway had two major functions: transmitting the digital data to computer through a serial port; forwarding user commands (such as start/stop, sleep, etc.) to nodes.

Generally speaking, based on this model, wireless distributed data acquisition system could work itself without manual intervention when the researchers had installed the equipment. The system had the both advantages of parallel system and distributed system – low costing, high accuracy. And what worth mentioned was that the wireless system improved the efficiency very significantly.

2.3 IMPLEMENTATION OF DATA ACQUISITION SYSTEM

By contrast, this paper tried both traditional parallel system and the wireless distributed system. Both the objects to be measured were disk structure composed of carbon fiber felt. There were 16 electrodes symmetrically placed on the surface of the disk. According the request of EIT experiment, we chose every electrode in turn as the driving electrode and collect the voltage signal from the others electrodes.

2.3.1 Implementation of parallel system

As mentioned above, we provided with current to the driving electrodes by using the constant current source and collected the output voltage signal from the others electrodes.

To ensure the accuracy of the parallel data acquisition system, we used two 8-channel dynamic signal acquisition devices PCI-4472, which manufactured by National Instrument (NI for short) to collect the voltage signal. The input current was supplied by the constant source. The connection between the PCI-4472 and electrodes was shield wire, which could reduce the signal attenuation. The PCI-4472 had the advantages such as 102.4 kS/s maximum sampling rate, IEPE conditionning, multiple-device synchronization, which made itself apply to voltage signal acquisition. The receiving end was a personal computer. Through the dedicated NI-DAQmx measurement services driver we could realize the interactions with the devices and computer software. The upper workstation software was written under the compiling environment of NI LabVIEW. In addition, the upper workstation software provided such functions as data reception, data processing, image reconstruction and data storage, etc.

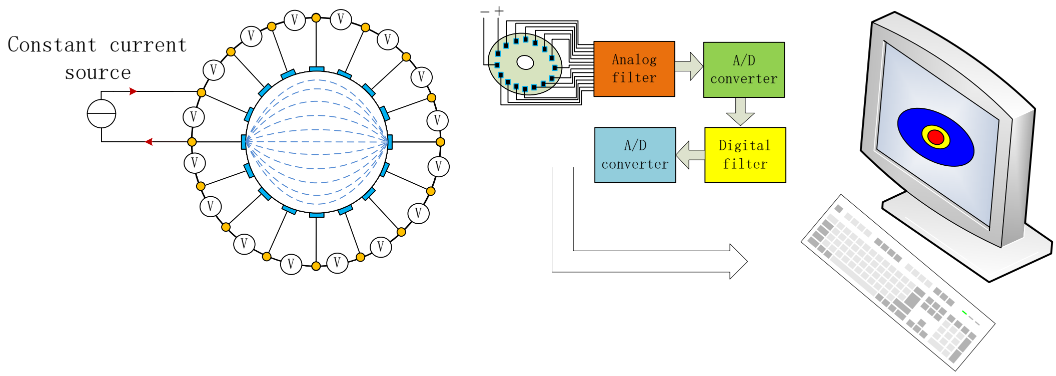


FIGURE 3 Model for parallel system

The brief view of parallel system is shown in Figure 3. From the Figure 3 above we would guess that a research must take apart all the wires and install them with a new sequence 16 times for a 16 electrodes EIT experiment. The total experiment period was average 2-3 hours on the premise that two researchers were conducting the experiment jointly.

2.3.2 Implementation of wireless distributed system

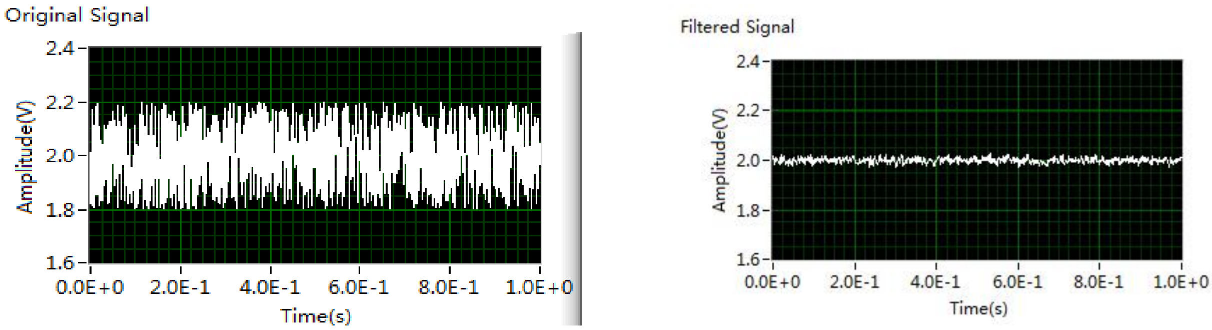
Nowadays, wireless technologies for short distance communication such as IR communication, Bluetooth, Wi-Fi, ZigBee [7] had caused wild attention of companies and research institutions. In consideration of the specific needs of the EIT data acquisition system, this paper chose the IEEE 802.15.4 as the wireless transmission protocol of the data acquisition system for its advantage of low power consumption, high reliability and low cost of development [8]. It was important to note that many other wireless transmission technologies as described above could also be used in EIT system but might increase production costs or bring other drawbacks.

The nodes of wireless distributed system developed our own could be used to provide constant current as input device or to collect the output voltage as the data acquisition and transmission device. All of the nodes used 24 bits high-precision A/D converters. But before the analog signal was converted to the digital signal, the signal should be filter to improve accuracy.

All of collected data would be processed in the filtering module. The main chip of the filtering module was STM32, which was a fully functional, powerful and cost-benefit. Through the a few adaptive filter algorithms (second derivatives Butterworth mainly) STM32 could filter lots of noises.

Figure 4 shows the comparison of signal before and after filtering. The Figure 4a was the waveform of voltage we collected only with the A/D convert from the electrodes, from which we could found that the voltage mixed with the white Gaussian noise. And convincingly, the amplitude of noise in the filtered signal had declined to about 0.03V from about 0.2V.

The gate way and the node which were both developed based on CC2530 microchip manufactured by Texas Instruments (TI for short) constituted a star network. Each node had been equipped with a 4.2V-430mAh Lithium polymer battery, which could afford the node continuously working over 10-12 hours. The batteries could be charged by common power supply. All of the wireless devices formed a star network. The model for wireless distributed system can be showed as Figure 5.



a) The original signal from electrodes without any filter b) The signal filtered by filter algorithms in STM32

FIGURE 4 Comparison of signals before and after filtering

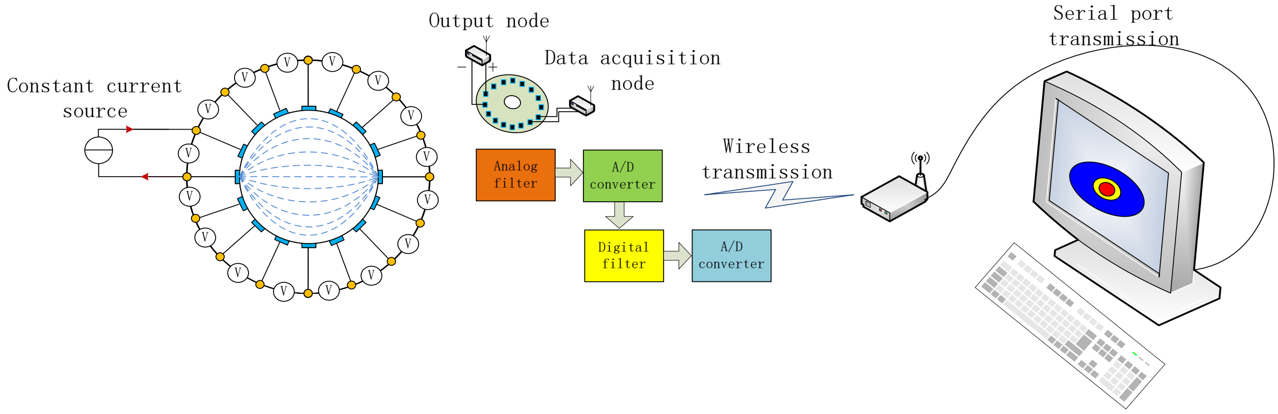


FIGURE 5 Model for wireless distributed system

Dimension of the wireless distributed node was 28mm×21mm×13mm. Its small size provided more possibility to be set as close to the electrode as possible. In most cases, the wire between node and electrode was not longer than 15 mm, which might cause amount of noise interference.

The wireless sensor network had the strong capacity of anti-interference, which benefited by the following designation (Li, Duan et al, 2007): the gateway used several ways including Clear Channel Assessment (CCA for short) to evaluate the environment and always chose the most optimal channel to build a network. During the communication the node adopt the CSMA/CA protocol: once the channel was busy the active node would retreat several machine period and tried again to transmit data (Meguerdichian, Koushanfar, Potkonjak and Srivastava, 2001). This process would go on until the data was sent successfully.

By using of the wireless distributed system, one need not to change wire connection when changing the driving electrode. And only one researcher could finish the experiment in a short time no more than 30 minutes. It was worth noting that the price of a couple of PCI-4472 was about 11000 dollars while the whole wireless distributed system was cost only less than 800 dollars.

3 EIT image algorithm

Based on the accurate data from the object to be measured, we need a way to solve the EIT problem. When injecting the constant current into the object, there would be a current field, which was similar to the quasi-state field. The electrical conductivity distribution function σ and potential distribution function φ satisfy the Laplace equation as:

$$\nabla \cdot \left[\sigma(x,y) \cdot \nabla \varphi(x,y)\right] = 0, (x,y) \in \Omega . \quad (1)$$

The basic and natural boundary conditions are:

$$\varphi(x,y) = f(x,y), (x,y) \in \partial\Omega , \quad (2)$$

$$\sigma(x,y)\frac{\partial \varphi(x,y)}{\partial n} = j(x,y), (x,y) \in \partial\Omega , \quad (3)$$

where Ω is the field, $\partial\Omega$ represents the boundary of the field, f stood for the potential of the boundary, j is the current density which flows into the field and n is the unit vector of the normal in the field [9]. This way, as it is shown in Equations (1-3), the problem of EIT iss translated to the solution to the partial differential equation of the electromagnetic boundary value problems.

Given the complexity of the field, it is very difficult to get the exact solution of the above partial differential equations. At present international researchers have proposed many algorithms such as back projection method, sensitiveties matrix algorithm and Newton-Raphson algorithm, etc. Among the common algorithms, Newton-Raphson algorithm has its own advantages, which bring its application more and more widely. This paper introduces the improved Newton-Raphson algorithm, which draws into the least square method to achieve the reconstruction of image.

3.1 THE IMPROVED NEWTON-RAPHSON ALGORITHM

In the previous studies Newton-Raphson algorithm held an important status in EIT problem. But an increasing number of researchers has found that estimate of initial resistivity distribution was limited strictly when solving in this algorithm. Moreover, the inaccurate solution in iterative process and the high time-complexity were also key flaws of Newton-Raphson algorithm [10]. Based on that, this paper drew into the least square method and introduced the improved Newton-Raphson algorithm.

By dividing the field in to N units, we could get n value of resistivity accordingly, which might be expressed as $\rho = \left(\rho_1, \rho_2, \cdots, \rho_N\right)^T$. Given the field was static, we might give reasonable hypotheses that the resistivity distribution was constant. So we would collect the voltage of adjacent electrodes $V_{ij}\left(i, j = 1, 2, \cdots, N\right)$. And at the same time, through the finite element we could get the calculated value $U_{ij}\left(\rho\right)\left(i, j = 1, 2, \cdots, N\right)$. So we define the optimal function as:

$$E\left(\rho\right) = \frac{1}{2}\left\|V - U\left(\rho\right)\right\|^2 = \frac{1}{2}\sum_{i}^{N}\sum_{j}^{N}\left(V_{ij} - U_{ij}\left(\rho\right)\right)^2 , \qquad (4)$$

$E\left(\rho\right)$ is the sum of the squares of the difference between the measured value and the calculated value of voltage.

The core problem of image reconstruction was to seek the optimal resistivity distribution, which yielded the minimum $E\left(\rho\right)$. At this point, we solved the problem by computing the partial derivative of $E\left(\rho\right)$ with the elements of ρ. Setting the partial derivative equal to 0, we receive:

$$F_n\left(\rho\right) = \frac{\partial E\left(\rho\right)}{\partial \rho_n} = -\sum_{i=1}^{N}\sum_{j=1}^{N}\left(V_{ij} - U_{ij}\left(\rho\right)\right)\frac{\partial U_{ij}\left(\rho\right)}{\partial \rho_n} = 0, \quad n = 1, 2, \cdots, N, \qquad (5)$$

$$F\left(\rho\right) = -U'\left(\rho\right)\left(V - U\left(\rho\right)\right) = 0 , \qquad (6)$$

where $F_n\left(\rho\right)$ is the partial derivative of $E\left(\rho\right)$ with ρ. $U'\left(\rho\right)$ is Jacobian matrix. Defining $U'\left(\rho\right) = J$, we get the elements of J using $\frac{\partial U_{ij}\left(\rho\right)}{\partial \rho_n}$.

According to Newton-Raphson algorithm, there ought to be the following equations:

$$\rho^{(k+1)} = \rho^{(k)} + \Delta\rho^{(k+1)} = \rho^{(k)} - \left[F'\left(\rho^{(k)}\right)\right]^{-1} F\left(\rho^{(k)}\right), \quad k = 0, 1, 2, \cdots, K, \qquad (7)$$

$$F'\left(\rho^{(k)}\right) = H\left(\rho^{(k)}\right) = J\left(\rho^{(k)}\right)J^T\left(\rho^{(k)}\right) - U''\left(\rho^{(k)}\right)\left(V - U\left(\rho^{(k)}\right)\right), \qquad (8)$$

where we may ignore $U''\left(\rho^{(k)}\right)$ for the reason that it was relatively much smaller than the others. So basing on the above equations we equation $H\left(\rho^{(k)}\right) \approx J\left(\rho^{(k)}\right)J^T\left(\rho^{(k)}\right)$ is satisfied. Immediately, the Equation (7) can be simplified:

$$\rho^{(k+1)} = \rho^{(k)} - \left[H\left(\rho^{(k)}\right)\right]^{-1}\left\{J^T\left(\rho^{(k)}\right)\left[V - U\left(\rho^{(k)}\right)\right]\right\}. \qquad (9)$$

With this, it was not difficult to find that the improved Newton-Raphson algorithm can make up the disadvantages in EIT. But we should also envisage the new problem in this improved algorithm – the difficulty and complexity of solving Jacobian matrix. So, this paper selected the Tikhonov regularization to make further progress on dealing with the problem.

3.2 TIKHONOV REGULARIZATION

Tikhonov regularization was designed for solving various ill-posed equations. The rationale of Tikhonov regularization was plugging higher-order eigenvectors which had been applied damping to model parameter for refactoring [11]. Usually, we achieved the damping by adding penalty functions. In this paper we defined the penalty function as $\alpha\left\|L\left(\rho - \rho_0\right)\right\|^2$. α is the parameter for refactoring. Then the Equation (4) (objective function) can be turned into equation:

$$E\left(\rho\right) = \frac{1}{2}\left\|V - U\left(\rho\right)\right\|^2 + \alpha\left\|L\left(\rho - \rho_0\right)\right\|^2 . \qquad (10)$$

Accordingly, Equation (9) is changed into equation (11) finally:

$$\rho^{(k+1)} = \rho^{(k)} + \left[J^T J + \alpha R^T R\right]^{-1} \times J\left(\rho^{(k)}\right)\left[V - U\left(\rho^{(k)}\right)\right] - \left[J^T J + \alpha R^T R\right]^{-1}\alpha R^T R\rho . \qquad (11)$$

With this, the problem is solved successfully.

3.3 IMPLEMENTATION OF THE IMPROVED NEWTON-RAPHSON ALGORITHM

As the most famous commercial data-analysis and visualization tool, MATLAB is widely used in EIT field. Through MATLAB programming we've successfully applied the improved Newton-Raphson algorithm to software. But it would be still cumbersome for users to enter data manually to the image reconstruction software. So, our final project was integrating the data processing software and the image reconstruction software. To achieve this goal more efficiently, we selected the following scheme as Figure 6.

The whole upper workstation software was written in NI LabVIEW. The software would receive the digital data from the gateway by serial protocol. Once the EIT experiment was over, it could convert the received data into a new data form, which was saved in a specified txt. Afterwards, the software would call the MATLAB script, which had been compiled previously to complete the reconstruction of image. By this way, when the researcher clicked "STARTING EIT" button, only he need to do was waiting to observe the image results. Fig 7 showed the operating software for wireless distributed system under the automatic mode.

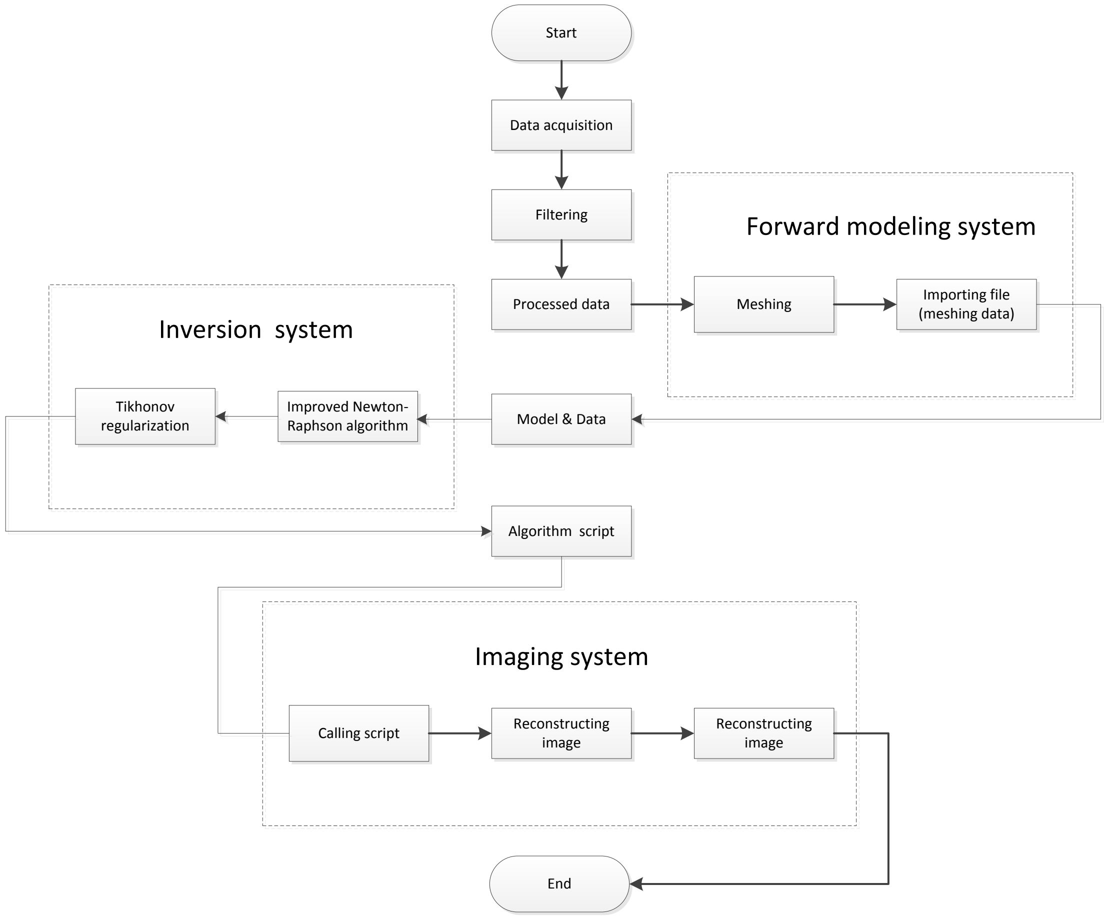


FIGURE 6 The flow chart of upper workstation software

4 Results and conclusions

As mentioned above, this paper tried both traditional parallel system and the wireless distributed system for compareson. Both the systems have used the improved Newton-Raphson algorithm to reconstruct the image.

As shown, images in the first row are the photos of the objects to be measured. Images in the second row are the result of the wired parallel system. Certainly, images of the third row are the result of the wireless distributed system. We'd made 3 disks structure composed of carbon fiber felt and conducted the experiment using the both methods twice for each disk. One disk among them was used for EIT experiments in the two cases of complete disk and the damaged disk, which are shown in Figures 8a and 8c.

From Figure 8 we can see that given the same image reconstruction algorithm, the image result of both systems are consistent with the object to be measured. Obviously, the differences between the parallel system and wireless distributed system seem very slight.

Considering the parallel system has consumed much more time and cost than the wireless distributed data acquisition system, we believe that the results have already shown that the wireless distributed data acquisition system is a successful, accurate and optimized for EIT experiment indeed. It is also proven that the improved Newton-Raphson algorithm could completely meet the demands in EIT experiment.

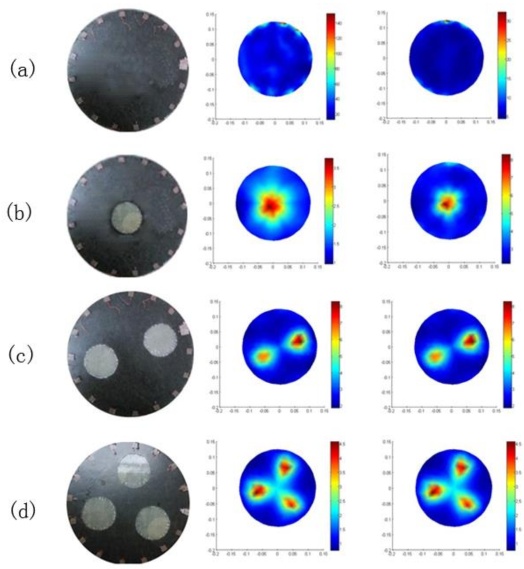


FIGURE 8 a) photo of the original object to be measured and the results of parallel system and wireless distributed system, b) photo of the object to be measured damaged in center and the results of parallel system and wireless distributed system, c) photo of the object to be measured damaged two areas and the results of parallel system and wireless distributed system, d) photo of center of the object to be measured damaged three areas and the results of parallel system and wireless distributed system

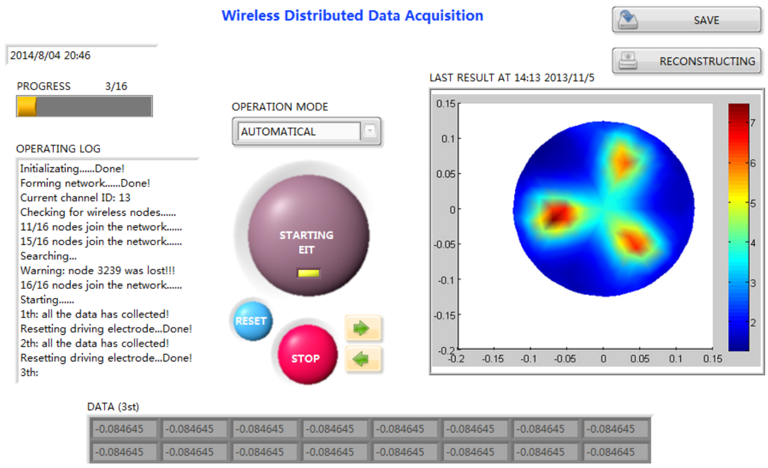


FIGURE 7 The upper workstation software for wireless distributed system

At last, this paper has taken the disks structure composed of carbon fiber felt for instant. In consideration of the advantages of wireless sensor network, we have every reason to believe that the wireless distributed data acquisition system can be used in actual projects more widely. On the other hand though, there are still some limitations in using the improved Newton-Raphson algorithm, it could not be denied that the algorithm has made some progress basing on the traditional algorithms. In any case, the encouraging results already indicate its promising future.

Acknowledgments

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