Electromagnetic Tomography for Medical and Industrial Applications: Challenges and Opportunities

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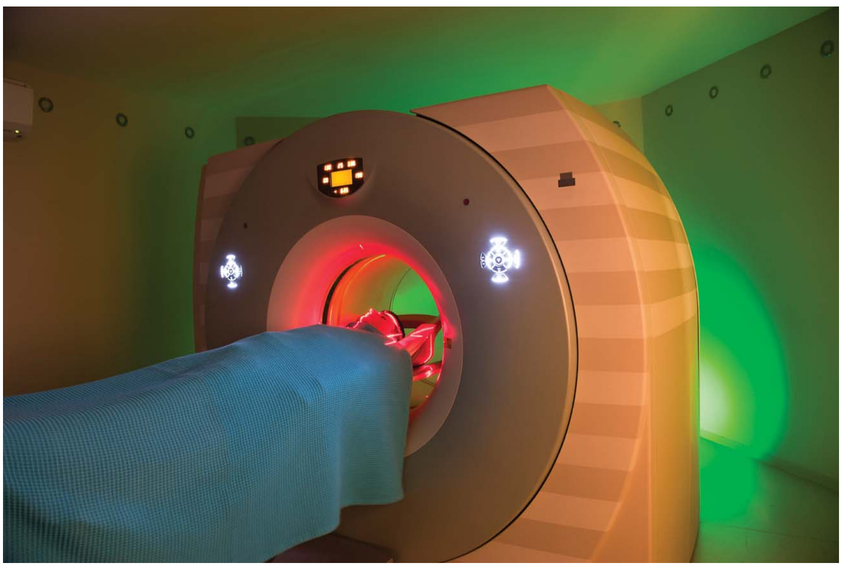

I. INTRODUCTION—WHAT IS TOMOGRAPHY?

Tomography is a technique that can create an image showing the internal structure of an object, preferably without causing any damage. The word "tomography" comes from the Greek words "tomos" which means "a slice, a section," and "graph," which means "image." Formal definitions of the word "tomography" in the Oxford English Dictionary and the Merriam-Webster's Medical Dictionary are as follows.

- "A technique for displaying a representation of a cross section through a human body or other solid object using X-rays or ultrasound."
- "A method of producing a three-dimensional image of the internal structures of a solid object (as the human body) by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures called also stratigraphy."

As seen from the above definitions, several tomography techniques already exist in the field, such as X-ray and γ-ray tomography. These are the so-called "hard-field" tomography, whose transmitting signal follows a straight line pattern. Hard-field tomography has been widely used in the medical field, however, the cost of

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such equipment is generally very high. And most of the traditional imaging systems contain radioactive sources, which may cause side effects in a patient, especially under long-term exposure.

Conversely, there are also "soft-field tomography" techniques that can be used in medical and industrial fields. The difference between hard- and soft-field tomography is that in soft-field tomography the transmitting field does not follow the straight line pattern anymore, and the signal distribution depends on the type of the excitation source. The nature of soft field is much more complex than the nature of hard field, which presents a great difficulty when computing the image reconstruction algorithms. Examples of soft-field tomography are electrical impedance tomography (EIT), electrical capacitance tomography (ECT), and magnetic induction tomography (MIT). These three are normally considered as "electrical tomography." The main advantages of the electrical tomography are that it is low cost and fast at the same time. The aim of the future development is to have a portable, battery-operated, electrical tomography device, which can be used in a medical field by a doctor giving an initial diagnosis in the area where the access of medical resources is difficult, or in an industrial field as a replacement of other imaging tools due to its cost-effectiveness.

MIT is the newest member in the electrical tomography family. MIT is a technique that uses electromagnetic fields to examine the passive electromagnetic property (PEP) variation of a material, which can potentially be used for many industrial/biomedical applications, such as two-phase flow process imaging, slung imaging, and brain diagnostics. In this point-of-view article, the latest progress of MIT, and its way forward into future, will be reviewed.

II. MAGNETIC INDUCTION TOMOGRAPHY

In electrical tomography, EIT and MIT can both be used for conductivity imaging. EIT is the oldest technique among the electrical tomography technology, and it is largely involved in many applications. However, the main disadvantage of EIT is that it involves attaching multiple electrode sensors around the surface of the imaging object. For example, in biomedical applications, in order to obtain a high-quality image, the sensors need to be attached at a regular intervals around a patient, which presents great difficulties as the position of the electrodes can be altered due to the movement of the patient. In contrast, surface electrodes are not required in MIT. In MIT, all the electrodes are replaced by coils, which do not touch the patient and can, therefore, offer a contactless feature, which is believed to be more suitable for applications in medical and other fields.

MIT is a relatively new technique compared to EIT and ECT. The first MIT concept was proposed in 1992–1993 [1], [2], whereas the first EIT report was published in 1978 [4]. The principle of MIT is based on the mutual inductance theory and the eddy current problem. Coils are used as transmitters and receivers in MIT. When a sinusoidal current is established in a coil, a changing magnetic flux is set up. This sinusoidal magnetic flux can induce a voltage across the terminal of sensor coils based on the mutual inductance theory. If the conductivity distribution between the transmitting and receiving coils is changed, the induced voltage at the sensor coils will be perturbed. By observing this perturbation, the "tomograph" of PEPs can then be generated by solving the forward and inverse problem. The architecture of the MIT system is similar to other electrical tomography systems. Fig. 1 illustrates a typical MIT system, which generally consists of the following:

- an array of evenly spaced coils that are arranged around the measuring object;
- the front–end electronics, for example, receiver buffers, driving amplifiers, and channel multiplexing switches;
- a data acquisition unit;
- a computer and the algorithm which can transfer the signals into MIT images.

All the imaging processing techniques, including electrical tomography, require solving two different problems, namely, the forward problem and the inverse problem [5]–[9]. Fig. 2 illustrates the difference between these two. In short, the forward problem is a simulation study that

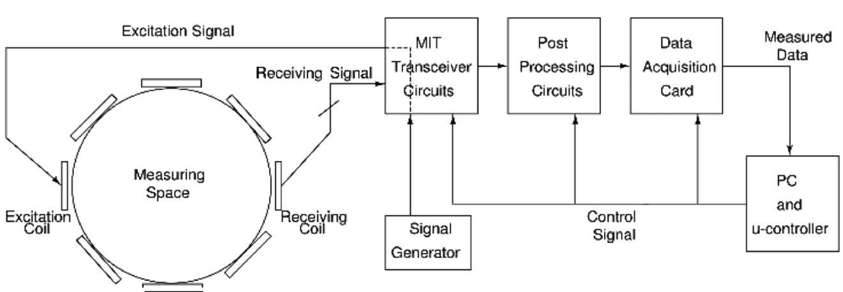


Fig. 1. ***A complete MIT system block diagram.***

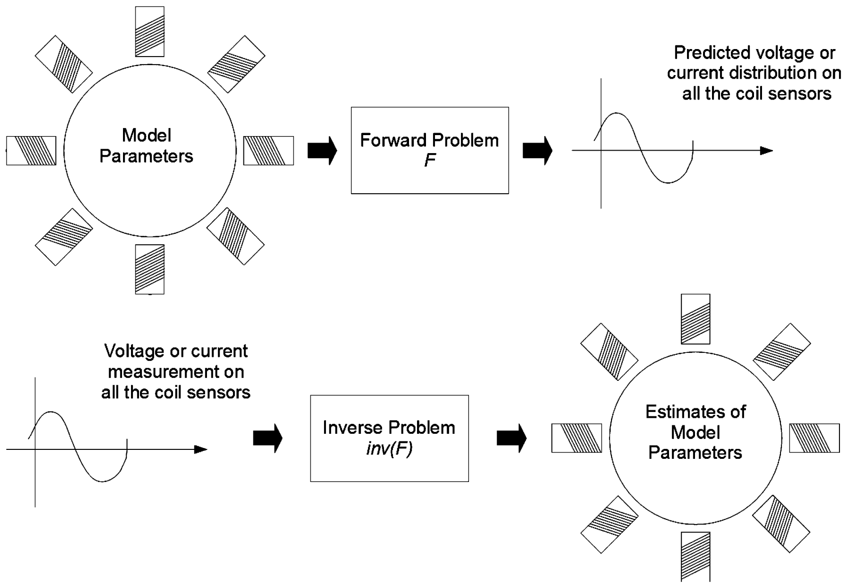


Fig. 2. ***Illustration of forward and inverse problem in MIT.***

determines the sensor behavior for a given PEP distribution. On the contrary, the role of inverse theories is to provide the best estimation of the unknown PEP distribution in the model based on the sensor measurements. In MIT, the differential forward model is expressed in terms of Maxwell's equations and Eddy current equations, and is then solved numerically using a technique such as the finite element method (FEM).

When the MIT forward model is simulated, the inverse solver will be used to obtain the reconstructed image based on the forward model. The inverse theory is typically the set of mathematical techniques that are used to extract useful real-world information from the physical measurements. It is a broad topic that can be implemented for all the imaging science technology. Since the MIT forward model is formulated as nonlinear model, its inverse algorithms are usually nonlinear as well. As a result, an update of the forward model is required in the inverse solver. However, in real-time applications, linear approximation is often presumed when solving the inverse problem, due to the huge computational resource required for nonlinear solvers.

III. CHALLENGES AND OPPORTUNITIES

Why is MIT so difficult to develop? When considering the forward model of the conventional medical imaging methods such as X-Ray CT and other "hard-field" tomography techniques, since their transmitting fields generally follow a straight line pattern, the change of the pixels' property (which cause the attenuation of the radiation beam) can, therefore, be "localized" to the area along the radiation beam path. This localization feature makes the forward and inverse models less complex in hard-field tomography. However, in MIT, because of the dispersed nature of the electromagnetic field (the transmitting field no longer follows the straight line pattern), the change in conductivity cannot be "localized" anymore and can cause signal perturbation on any measurement set, which makes the MIT model more complicated. Besides the nonlocal properties lying in the inverse problem, the forward problem computation for MIT itself is much more challenging than the other tomography methods, such as EIT and ECT, since *curl* operators are involved in the calculation of the forward model [8].

What is worse than the nonlocalization properties is the ill-posed nature of MIT. The inverse problems of X-Ray CT can be defined as well-posed problems, which means that a unique and continuous solution must exist for a given set of physical models. However, it is known that many imaging techniques in science and technology are not necessarily well posed, for example, electrical tomography. In MIT, the inverse problem is typically an ill-posed problem. The definition of an ill-posed problem is that the solution is either not unique, not existent, or not continuous [3]. The continuity is usually the biggest problem for solving the inverse problem for MIT: any small perturbation from the sensor reading can cause large perturbation of the solution, as the number of unknown conductivity pixels is generally higher than the number of measurements.

These difficulties in the forward/inverse problems are the principal reasons that make MIT so difficult. However, There are several stabilizing techniques, for example, regularization, which can be used to change the nature of the MIT model from an ill-posed problem to an almost well-posed problem. These stabilizing methods must be considered when designing MIT inverse solvers.

In general, MIT systems can be divided into two categories: high-conductivity imaging and low-conductivity imaging. Since the conductivity properties of the target detecting objects in these two categories differ hugely, the design for each stage of such MIT hardware systems requires different focuses.

A. High-Conductivity MIT Imaging

- Tracking ferrite labeled powder in the separation processes.
- Foreign body detection (metal) in food, textiles, pharmaceuticals, and packaging industries.
- Molten metal casting process, e.g., liquid steel flow monitoring.
- Nondestructive testing (NDT) for material characterization, for example, the surface crack detection, composite carbon fiber material examination, and other functional imaging.

At the moment, the MIT researchers still mainly use this technique as a conductivity imaging tool. This automatically brings up several industrial MIT applications which involve the conductive material operation. MIT can be implemented in the processing industries, as accurate process monitoring is often required in order to perform the best operation control and maintain a high-quality process. Many NDT applications can also potentially be realized using MIT, as its contactless feature makes it more suitable in industrial applications, due to the fact that the direct contact with the imaging object is often not allowed in the industrial environments.

In food processing industries, metal detectors are often used for foreign object contamination checks in order to provide compliance with food safety inspection standards. However, most of the metal detectors on the market can only provide the binary information which indicates the presence of the conductive material in the product. By using the MIT technique, the system can further provide the location and properties of the contamination, which can help handling the postprocessing work in a more efficient way. Because of the MIT's low-cost, high temporal resolution, and contactless features, several industries can benefit from the future MIT development.

B. Low-Conductivity MIT Imaging

- Brain images for stroke detection—the advantage of MIT is that the magnetic field can easily penetrate through the skull, whereas for EIT, the skull acts as a resistive barrier.
- Two-phase flow process imaging in pipelines, for example, monitoring of bulk ionized liquid in pipelines.
- The inductive measurement of wound conductivity—performing impedance measurements of a wound from electrodes is very difficult as the surrounding skin is often uneven and in poor condition.
- Lung imaging—EIT has been extensively used in the lung imaging applications; it is also an interesting area for MIT to be explored, where MIT's contactless feature can make the examined process less invasive.

At present, most of the medical imaging tools can only be found in a well-equipped hospital and usually involve high cost. The fast and low-cost advantages of the MIT technique can certainly bring some new developments into the medical industry. In the near future, a portable and low-cost MIT system can potentially be developed and, therefore, realize the so-called "point of care" diagnosis. It is an extremely challenging task, due to the small contrast and the unobtainable baseline data. However, the success of the research could produce a major step forward in the medical imaging techniques and significantly improve the availability of medical resources. With a portable and battery-operated MIT device, a doctor will be able to give a medical diagnosis in a rural area where a well-facilitated hospital is not available. Many brain diseases, such as acute cerebral stroke, brain tumor, and brain oedema, can be diagnosed at an early stage if the point of care examination can be realized. People (especially in the developing countries) can benefit greatly, and it is believed that the number of casualties due to brain damages could be largely reduced because of the development of the MIT project.

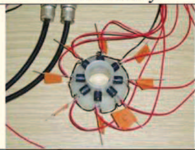
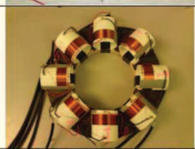
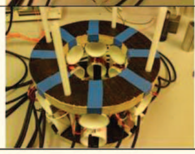
IV. PROGRESS ON MIT SYSTEM DEVELOPMENT AND IMAGING RESULTS

As stated before, MIT is a noninvasive, contactless tomography technique that can visualize the conductivity distribution within the measuring space. At the Engineering Tomography Laboratory, University of Bath (Bath, U.K.), several MIT systems have been developed: Bath Mk-I, Bath Mk-II, and Bath Mk-II 3D [10], [12]–[14]. For the industrial systems, as the conductivity contrast between metal (high conductivity) and air (insulator) is huge, this feature makes system design slightly easier than the medical system. Table 1 shows pictures of all three industrial models, with specifications of the sensor array.

From the systems above, we can image any high-conductivity objects with various sizes. The diameters of the screws shown in Fig. 3 range from 3 to 19 mm. With the 3-D system, the height information of the object can be obtained as well. Fig. 3 shows the reconstructed images for the aforementioned systems.

MIT system design for high-conductivity applications is easier because of the higher contrast. For medical applications, due to its low-conductivity features (< 10 S/m) of the biological tissue, the magnitude of

Table 1 Industrial MIT Systems Developed at the University of Bath

System Model	Sensor Array	Array Specifications
Bath MIT Mk-I		• 8 Channels • Measuring Space (2D): 20 mm diameter • Commercialized ferrite-core sensor
Bath MIT Mk-II		• 8 Channels • Measuring Space (2D): 110 mm diameter • Hand wound 50 turns air-core coil sensor
Bath MIT Mk-II 3D		• 16 Channels • Measuring Space (3D): 110 mm diameter, 125 mm height • Hand wound 50 turns air-core coil sensor

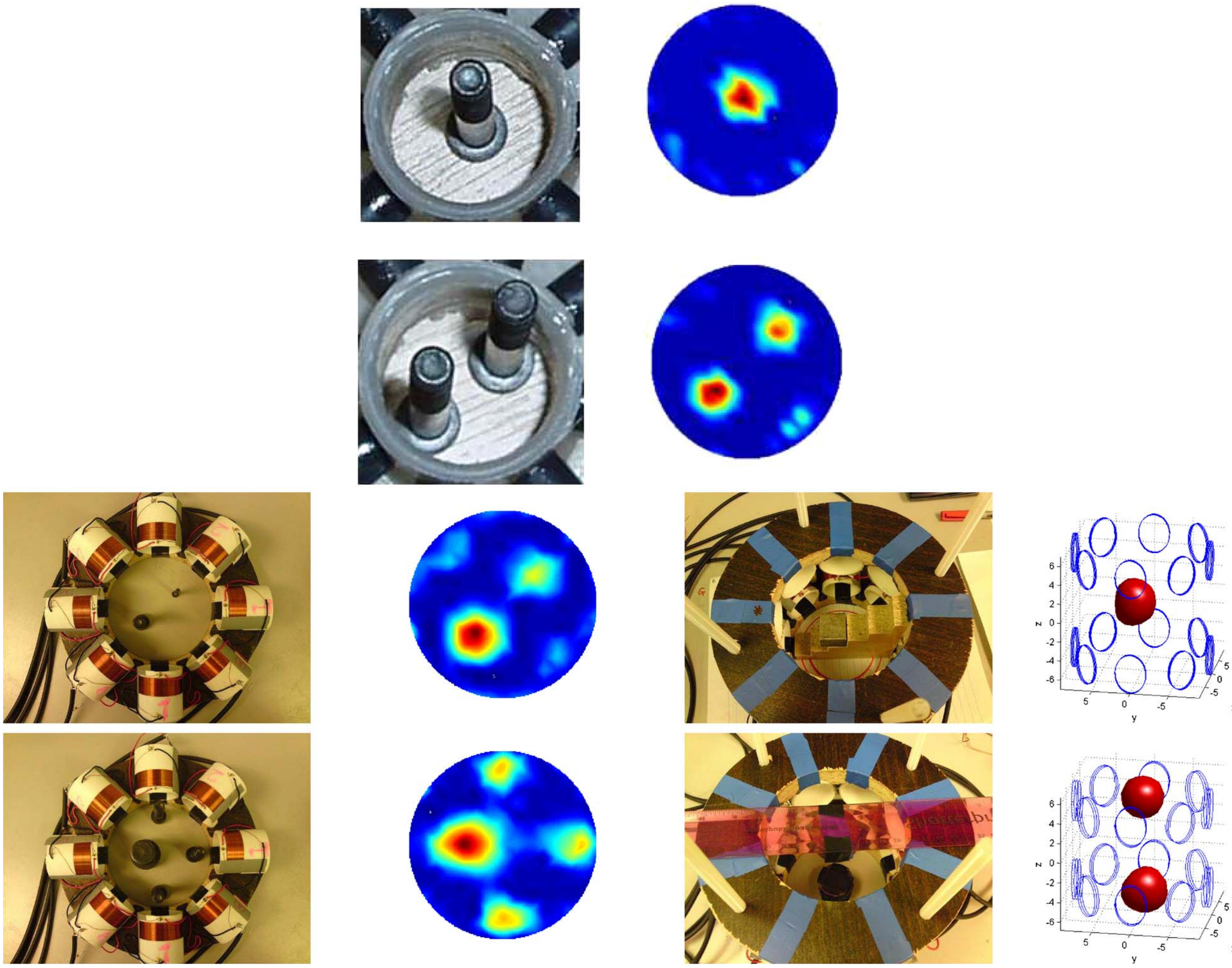


Fig. 3. ***Reconstructed images from Bath Mk-I, Mk-II, and Mk-II 3-D systems (images from [10]).***

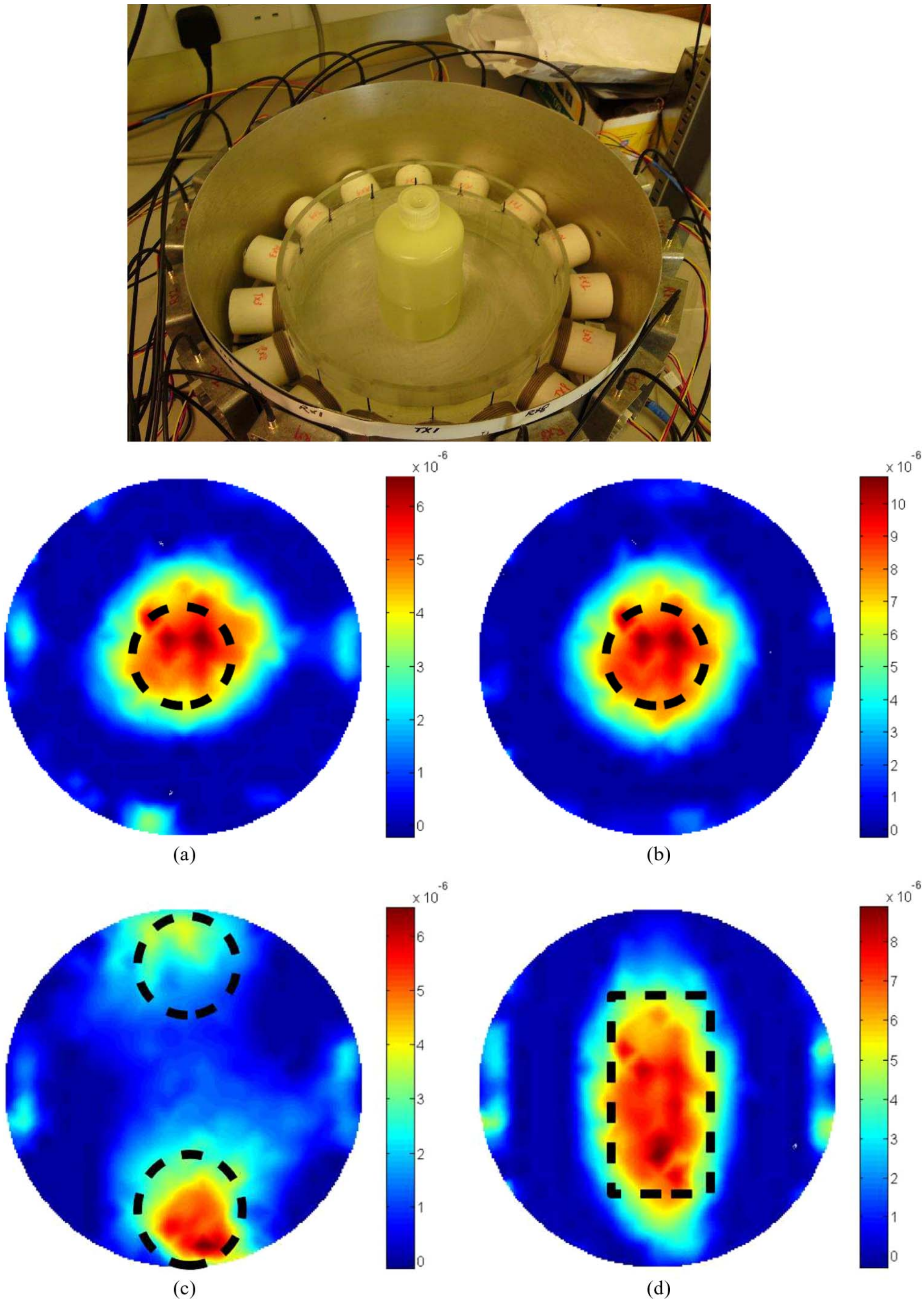


Fig. 4. ***Reconstructed images of the low-conductivity saline solution using the Bath MIT Mk-III system: (a) 3% saline at the center; (b) 5% saline at the center; (c) 3% and 5% salines placed at the top and the bottom positions, respectively, and (d) 5% saline bottle placed in the vertical position.***

signal perturbation is several orders less than the acquired signal in industrial applications, which generally monitors high-conductivity materials ($> 10^6$ S/m) such as metal. The signal perturbation induced by biological samples is generally $< 1\%$, which results in a much more challenging task for development.

An MIT system for medical applications (Bath MIT Mk-III) was also developed [11]. A field-programmable gate array (FPGA) module is implemented to largely improve the data sampling performance, which can be used to detect the extremely small perturbation caused by low-conductivity objects, as shown in Fig. 4. The measuring objects in this experiment were saline solutions with different concentrations: 0.9% ($\sigma = 1.58$ S/m), 3% ($\sigma = 2.31$ S/m), and 5% ($\sigma = 7.26$ S/m) by weight. The 0.9% medical saline was used as the measuring background (normal biological tissue), and the 3% and 5% salines are used to represent the abnormal tissue (e.g., tumor) whose electrical conductivity has varied due to an infection.

All the results shown in Figs. 3 and 4 are very promising. The position, the shape, and the size of the measuring targets are all correctly determined in the reconstructed images. The image resolution for electrical tomography is generally lower than for the hard-field tomography, due to the nature of the electromagnetic field. However, it can still be seen that MIT is a very useful imaging tool that has great potential to be applied in many different areas, in both industrial and medical applications. We have also established a new application for low-conductivity MIT imaging for two-phase flow imaging [15].

V. WHAT TO DO NEXT?

Although there have been several active research groups continuing the MIT research, there has not been any huge breakthrough on its application for the past few years, perhaps due to insufficient interaction between different disciplines. At the current state, MIT is still considered as an "academic research" and not much collaboration has been made between academic institutions and the industrial companies. MIT is a new technology, however, the authors believe that the current MIT development has matured enough to be applied into real-world applications. MIT is an imaging tool, hence the room for applications can potentially be very wide and can even enable interaction between different fields. It is not a standalone subject; knowledge from different disciplines is required to successfully develop an MIT system and algorithms, as the hardware/software design can vary significantly according to the target applications. The future trend of tomography researches must be more "application oriented" in order to derive further innovations needed. To realize this, a cross-discipline team is essential, and team members must come from different backgrounds and have the ability to work together with other researchers and potential users.

In summary, MIT's low-cost and noninvasive features can offer great excitement and potential to address many challenging problems that exist in the current industrial/medical applications. The foundation development of MIT has been made in the past ten years. Many more advancements can be expected in the next decade, including the first commercialized MIT system for industrial or medical application. It will certainly contribute some impact to the current imaging technology. ■

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