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Electrical Impedance Tomography for Embedded Sensing and Nondestructive Evaluation: A Perspective for Advancement

Tyler N. Tallman

School of Aeronautics and Astronautics, Purdue University
701 W. Stadium Avenue, West Lafayette IN, 47907

ABSTRACT

Electrical impedance tomography (EIT) is the process of mapping the spatially varying conductivity distribution of a domain. In the last couple of decades, EIT has been explored for the nondestructive evaluation (NDE) and embedded sensing of structures and materials. The supposition in these applications is that many materials have electrical conductivity that responds to deleterious effects; thus, EIT can conceivably be used to detect and localize these effects. This field, however, has become saturated with results that do little to transition EIT out of the proof-of-concept phase and into meaningful practice. As an antidote to this stagnation, a perspective is herein provided on critical challenges that need to be addressed to make EIT truly viable for NDE and embedded sensing.

Keywords: Electrical impedance tomography, nondestructive evaluation, embedded sensing, inverse problems

INTRODUCTION

Electrical impedance tomography (EIT) is a non-invasive method of spatially mapping the electrical conductivity distribution of a domain based on voltage-current measurements collected at the boundary of the domain. Because material removal, breakage, cracking, strain, etc. change the electrical transport properties of many materials, this modality has been investigated for nondestructive evaluation (NDE), structural health monitoring (SHM), and embedded sensing (e.g., impact damage detection in a carbon fiber/epoxy composite, see Figure 1). Even though EIT has been researched since the 1970s, initially as a benign biomedical imaging modality [1], the first applications of the traditional EIT formulation for damage imaging was by Lynch and colleagues in the mid-2000s on nanocomposite skins (e.g., reference [2]). Since then, EIT has received increasing attention for materials imaging as summarized in a recent topical review [3]. As a nomenclature aside, the materials community actually makes use of electrical *resistance* tomography (ERT) to map DC conductivity. *Impedance* implies frequency-dependent properties. Nonetheless, EIT is the standard verbiage in the materials community, so it is likewise adopted herein.

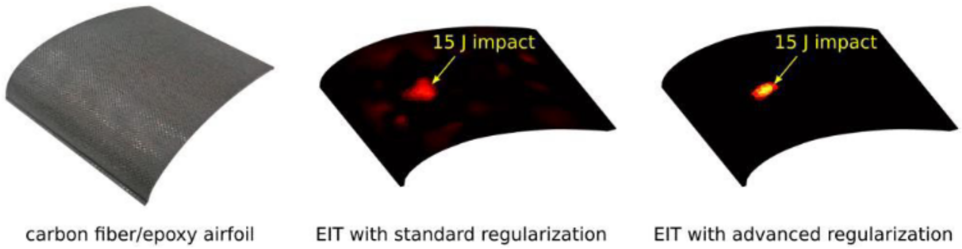
At its heart, EIT is an inverse problem that can be stated as follows: Given some experimentally observed voltage-current relationship at the boundary of a domain, what is the conductivity distribution of a (typically finite element) model that gives rise to the same boundary voltage-current relationship? The EIT inverse problem has been well studied by the mathematics community and is known to be severely ill-posed [4]. Consequently, regularization–the application of assumptions about the solution space–is needed to recover a physically meaningful solution.

Despite the appeal of EIT for NDE, critical challenges persist with this modality that prevent it from seeing adoption in practice. Unfortunately, these challenges do not seem to be attracting much attention from the research community. Rather, the emphasis currently seems to be on overly simple proof-of-concept studies applying EIT to flat plates using standard inversion algorithms. This is important because EIT does indeed have unique potential for NDE, but this potential will never be realized unless these challenges are addressed. Thus, this perspective serves as a short summary of these challenges and a call to action to address them.

STRENGTHS AND WEAKNESSES OF EIT

There is no one-size-fits-all NDE technique, and EIT is certainly no exception. If we want to make a case for investing in advancing EIT into practice, it worth first summarizing its strengths and weaknesses. This discussion is meant to be irrespective of the challenges currently facing EIT (i.e., even if the challenges are all solved, these strengths and weaknesses persist because they are inherent to EIT). Strengths of EIT include:

- Ease of accessibility: EIT needs only low-cost, readily available, and easily multiplexed electrical measurements (e.g., Arduino platforms costing only hundreds of dollars have been successfully used).
- Potential for on-board sensing: Electrodes can be built into or onto the component being inspected for on-board sensing, which is certainly not feasible for other tomographic modalities (e.g., x-ray CT).
- Physiologically benign: Unless excessively high electrical currents are used, EIT is safe to the operator.
- Ultra-high temporal resolution: Because no moving parts are used in the imaging process, EIT's temporal resolution is only limited by the speed of the current injection and data acquisition system.
- Sub-surface imaging: Much NDE is limited to surface or near-surface inspections. EIT can visualize sub-surface effects.
- Large-scale imaging: EIT can be used on very large scales (kilometers for some geospatial applications [5]), which is not feasible for other tomographic modalities like x-ray CT.



carbon fiber/epoxy airfoil EIT with standard regularization EIT with advanced regularization

Figure 1. Representative EIT results for impact detection on a carbon fiber/epoxy airfoil (left). Middle: EIT using standard smoothness-promoting regularization. Right: EIT using advanced regularization. The advanced image is markedly superior–better localization, fewer noise artifacts, etc. Original data for images taken from reference [6]. Advanced regularization image based on reference [7].

On the other hand, weaknesses of EIT include:

- Low spatial resolution: EIT is a diffuse imaging modality. Physically, this means electrons move through the material following a path of least resistance, which is generally not a straight line. Practically, this means that EIT will never generate images near the quality of modalities like x-ray CT.

- Mathematical complexity: The mathematics of EIT are certainly not prohibitively complex, but successfully using the method does require familiarity with the underlying theory. Because of this perceived barrier to entry, many researchers opt to use the open-source EIT code EIDORS [8], misuses and abuses of which can result in significantly sub-standard or even outright non-sensical images.

- Ineffective on non-conductive and highly conductive materials: Like eddy current testing and magnetic particle inspection, there is a hard material-based limit on EIT: Non-conductive materials are simply not viable. Highly conductive materials (e.g., metals) are also challenging because current easily propagates around defects without causing measurable boundary voltage changes. Conductive composites (e.g., carbon fiber/epoxy) and conductive filler-modified and semi-saturated cements have been most studied so far.

AREAS REQUIRING ADVANCEMENT

As summarized above, EIT has unique potential for continuous, minimally invasive, sub-surface, and embedded sensing at large-scales. Even though it cannot compete with, for example, x-ray CT in terms of spatial resolution, x-ray CT will also never be able to do large-scale and continuous embedded sensing. Hence, tradeoffs exist when comparing NDE modalities, and the unique strengths of EIT motivate continued work in this area. Critical barriers are preventing the meaningful advancement of EIT, however. These barriers are discussed below.

- Extension to complex shapes: The overwhelming majority of work on EIT is done of flat plates that are utterly unrepresentative of real structural components. This may be a consequence of biomedical EIT also being predominantly 2D, wherein a cross-section of the patient's conductivity distribution is desired (hence the "tomography" in EIT). There is no longer any doubt that EIT works on flat plates; work on plates should therefore cease unless an appreciable new complexity is introduced (e.g., probability of detection studies, multi-frequency imaging, new regularization, etc.) and the use of a plate is intended to control extra variables when exploring the new complexity. There have been a few studies applying EIT to non-planar shapes [6] [9], but these used a direct extension of 2D EIT to a 3D formulation (i.e., reconstructing the conductivity distribution on a tetrahedral mesh rather than a triangular mesh). The challenge with this approach is that the number of elements in 3D meshes can quickly explode, making the EIT inverse problem computationally prohibitive to solve. Work is needed to develop computationally efficient algorithms for complex shapes. An excellent example can be found in the work by Jauhiainen et al. [10].

- Advanced defect and material-specific regularization: Regularization is necessary for solving the EIT inverse problem. Commonly used regularization by the materials imaging community includes the identity matrix, the discrete Laplace operator, and, less commonly, total variation regularization (rarely with ℓ_1-error and regularization norms, however [11]). This is problematic because these regularization methods are only loosely connected to the physics of materials and justifiable after-the-fact; we expect strains to be smoothly varying, damage to be discontinuous, etc. A better approach would be to build the precise physics of material-specific damage types into the regularization. More advanced regularization methods are well studied by biomedical and mathematical practitioners of EIT, but these have yet to see much use in the materials community. An example of the significant potential effect of advanced regularization is shown in the right-most portion of Figure 1 for imaging of impact damage to a carbon fiber/epoxy airfoil.

- Robust electrode integration and compensation for electrode drift, malfunctioning, etc.: Currently, electrodes are applied to materials as an afterthought using, for example, materials like silver paste and copper tape or combinations thereof. These kinds of electrodes, though effective for proof-of-concept, are certainly not likely to survive for long-term, environmentally exposed embedded sensing (even letting silver paste + copper tape electrodes sit in a laboratory setting for several days can cause them to degrade to the point of not reliably working). Further, it is not understood to what extent factors like electrode drift impact EIT imaging (i.e., electrical measurements varying over time due to aging of the electrodes). This is important because the EIT inverse problem, being ill-posed, can be highly sensitive to discrepancies between model-predicted and experimental electrode behavior. Thus, either new models beyond the currently used complete electrode model (CEM) are needed to account for drift, or electrodes need to be developed that do not drift. Additionally, it is possible that electrodes break or cease functioning during long-term embedded sensing. Strategies are therefore needed to account for faulty electrodes. The use of ℓ_1-error terms in the EIT inverse problem has potential in this regard, but solving the inverse problem with ℓ_1-error terms increases its complexity and is not often used by materials practitioners of EIT [11].

- Multi-frequency methods to eliminate time-difference imaging: Existent studies on EIT for NDE and embedded sensing make almost exclusive use of time-difference imaging. Time-difference imaging means that two sets of electrical measurements are collected–one before a damage event and another after a damage event–such that the EIT inverse problem seeks to reproduce the conductivity *change* between those two times. This is in contrast to absolute imaging, which seeks to reproduce the actual conductivity distribution at any particular time. Time-difference imaging is often a practical necessity in experimental EIT because sources of error common to both times (e.g., experiment-to-model electrode misplacement or shape discrepancies, system noise, etc.) largely subtract out, thereby greatly improving image quality. This presents a problem for NDE, however: Damage detection then requires knowledge of a prior state, which may not be available for first-time inspections of aging structures or may no longer be valid due to factors such as electrode drift or malfunctioning (see above). Compare this requirement to modalities such as x-ray CT, which does not require prior measurements to image the current state, and it is easy to see how time-difference EIT is not desirable. Fortunately, a potential solution exists. Biomedical practitioners of EIT face the same problems regarding electrode placement and domain shape uncertainty (the latter is arguably
- much more of a problem in biomedicine since people, unlike structures or components, rarely conform to quantifiably known shapes). To overcome this challenge, biomedicine makes almost exclusive use of multi-frequency or frequency-difference imaging methods. That is, because materials exhibit frequency-dependent transport properties, EIT measurements are collected at two different frequencies such that an image of the difference between those frequencies can be generated. There is no obvious reason this same approach cannot be done in NDE applications of EIT, but it has not yet been much explored by the materials imaging community.

SUMMARY AND CONCLUSIONS

In summary, this perspective has outlined what the author perceives as critical limitations that are keeping EIT out of more widespread practice for NDE and embedded sensing. These limitations include extension to complex shapes that are representative of real structures and components, lack of advanced regularization methods for materials and defect-specific imaging, development of robust electrodes and an understanding of difficulties associated with long- term electrode integration, and the need to embrace multi-frequency methods to eliminate the need for baseline measurements in time-difference imaging. Despite these limitations, it is worth reiterating that EIT does indeed have unique strengths–it has a low entry barrier, has potential for on-board sensing, is physiologically benign, has potential for imaging of extremely fast events, can generate sub-surface images, and can work on large structures.

Thus, it is concluded that while EIT is certainly not a one-size-fits-all modality (then again, nothing is), its unique strengths are deserving of effort to overcome the limitations outlined herein.

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