Developments in open-source tools for microwave breast imaging

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***Abstract*—Open-source models, datasets and toolboxes are becoming increasingly common in the microwave breast imaging literature, including numericial breast models, simulated and experimental datasets and imaging and analysis tools. These tools lower the barrier to entry for researchers interested in radar-based breast imaging, and also present the opportunity to test algorithms and approaches on multiple datasets with different advantages and limitations. In this work, recent developments in open-source tools for radar-based breast imaging are reviewed. Moreover, uses of the MERIT toolbox and the BRIGID dataset are examined and recent developments highlighted. Finally, gaps in the open-source landscape in terms of simulation and antenna design and standardised approaches are identified.**

I. Introduction

There is a long history of open-source tools and shared resources relating to microwave breast imaging including numerical breast phantoms, methods for experimental phantoms and shareable phantoms [1]–[3]. In the past five years, four open-source imaging and analysis toolboxes are now available [4]–[7] with two corresponding databases [6], [8].

The profileration of new open-source simulation and experimental tools presents opportunities and challenges in terms of lowered barriers to entry for new researchers and the potential to test and develop on multiple platforms simultaneously. However, in the absence of standardised tools, approaches or frameworks, many of the new analyses use similar but different metrics and analyses. These differences make comparisons between studies difficult, even when studies use the same data.

In this work, additions and extensions to the MERIT toolbox are presented along with an analysis of the studies using the various open-source datasets. Based on these extensions and uses, the current state-of-the-art of the open-source tools and the key gaps in the open-source pipelines are reviewed and discussed.

The remainder of this work is structured as follows: new open-source tools are discussed in Section II with particular emphasis on datasets, test platforms or imaging and analysis toolboxes; uses of and advances in the MERIT toolbox are presented in Section III; and gaps in the open-source landscape and future work discussed in Section IV.

II. New Open-source Tools

In this section, open-source datasets and imaging and analysis tools are reviewed. Many additional resources exist for the design and fabrication of experimental phantoms as reviewed in [6], [8], however, these are not included unless an accompanying dataset exists.

Two microwave imaging datasets are currently available:

- the BRIGID phantoms presented in [4], [8];
- and the University of Manitoba Breast Microwave Imaging Dataset (UM-BMID) presented in [6].

Both datasets have accompanying imaging code and reference examples, and both have been used by other researchers in the field, among others [9]–[12]. Several generations of UM-BMID have been released with updated phantoms and slightly different acquisition.

BRIGID uses a conformal array with flexible microstrip antennas contacting solid, poly-urethane phantoms directly and without a coupling medium. UM-BMID uses rotating, double-ridged antennas with liquid phantoms of varying complexity with some solid elements. Both systems can be used to collect multistatic information through repeated bistatic acquisition, but UM-BMID antennas can be rotated to arbitrary positions in the acquisition plane and the BRIGID antennas positions are fixed in a radome.

In part due to the system configurations, both BRIGID and UM-BMID use different phantom designs. UM-BMID uses 3D printed shells filled with liquids of the appropriate dielectric properties. The shell shape and internal contents are derived from MRI images. Spherical glass bulbs were used as tumour analogues, where the glass bulb walls were less than $1\,\mathrm{mm}$ in thickness, and the other shells were $2\,\mathrm{mm}$ in thickness. Due to the nature of the construction, the phantoms do not contain a skin layer, however, as the phantoms are suspended in air, there is a reflection caused by the air-phantom interface, although potentially not as large as from the equivalent skin.

In contrast, the BRIGID dataset are solid, perfect hemispheres with a $2\,\mathrm{mm}$ skin and interiors containing varying amounts of fibroglandular-mimicking tissues and tumours. The proportions of adipose-mimicking tissues to fibroglandular-mimicking tissues are based on values found in the literature [13] but individual phantoms are not based on particular clinical images such as in UM-BMID. The flexible antennas contact the skin layer directly, causing a realistic skin reflection.

Of the four imaging and analysis toolboxes, the MERIT toolbox has been primarily used with the BRIGID dataset [4], the UM-BMID code primarily used with the phantoms [6].

Other reference implementations of relevant imaging algorithms are distributed with a text-book [5] and useful segmentation and analysis functions are available in [7]. However, all the toolboxes and frameworks are generalisable and usable with other open-source or custom-generated datasets.

III. Uses and Advances in MERIT

The MERIT toolbox has been used by a number of groups worldwide since publication in [4] in 2018 for beamformer comparison studies in [12] and similar studies. At the time of publication, the MERIT toolbox contained a full implementation of the steps needed for microwave breast imaging, including a generalisable data model with minimum requirements for scan data, imaging domain, propagation models and beamforming. The toolbox also contained convenience functions for visualisation of the images, including converting between internal image representations and volumetric arrays. However, the toolbox contained limited model-based and experimental testing, few reference algorithm implementations and little discussion of quantative metrics for analysis.

To address these gaps, the toolbox has been expanded with a number of useful and generalisable functions and features. Firstly, while the testing framework was implemented, the number and scope of the tests has been increased, including unit testing of individual and generalisable signal processing functions, and model and integrating testing of the full imaging tool chain.

Secondly, the number of algorithms available has been expanded, including convenience functions to facilitate skin and artefact removal algorithms, generalisable beamforming functions and specific implementations of beamformers from the literature. Thirdly, the number and generalisability of the quantative metrics available has been expanded. As no agreed standard exists in the literature, a number of convenience functions are also available for implementation of new metrics.

IV. Discussion

Despite the welcome increase in the number and nature of the open-source tools available to the microwave breast imaging community, a number of challenges exist in integration and some gaps exist in the toolchains. Firstly, from a technical perspective, the majority of open-source imaging code has been developed and released with specific databases. While the tools are generalisable, few guides or functions exist for loading other databases, comparing results between databases or reference implementations for all available datasets using the same toolbox. While not a limiting factor to adoption, the opportunity for cross-testing and sharing of resources is not used. Furthermore, there is limited use of modern research software best practice and little investigation of formal verification, model-based testing and other testing techniques for software development in the absence of gold standards.

Secondly, in terms of the open-source environment, there are several gaps in the landscape. Although the majority of antennas used in operational microwave breast imaging systems are published, no open-source or configurable antenna models exist for new simulated or experimental data generation. Easily configurable environments would enable more substantial reuse of the series of numerical phantoms that are available for both testing and development. Once data is generated or acquired however, several complete toolchains can be used for processing and analysis, and the suite and quality of these tools continues to increase.

Moreover, high quality data for aspects of the microwave breast imaging steps are not always available: for example, testing and the development of artefact and skin removal algorithms is difficult as little suitable data exists and generating such data with finite-difference time-domain (FDTD) models with $1\,\mathrm{mm}$ resolution as is normal may be too coarse. Similarly, developing or designing hardware acqusition systems is difficult, as no guidelines exist for optimising the number or placement of antennas, the type or the frequency range.

Thirdly, the increase in data availability has enabled and allowed researchers from other fields and experts in machine learning to evaluate algorithms for microwave breast imaging and detection. However, few guidelines exist for suitable approaches to training and testing of algorithms using the publicly available datasets, and no investigations of the opportunites to exploit both datasets to increase data availability have been published. Configurable numerical phantoms have been released which could supplement existing experimental data for training, testing and validation.

Similarly, adaption of these toolboxes to medical microwave imaging more broadly is not common. Due to the lack of easily adaptable toolchains for data generation of the breast and other areas, this makes it more difficult to use the extensive toolchains generated for microwave breast imaging in other medical microwave applications.

In summary, although the open-source toolsuite for microwave breast imaging is large and powerful, there are some barriers to adoption of each individual tool and little reuse, adoption or standardisation across the community. Improved toolchains and modelling support for data generation, including for other body parts, and integration of data generation with reconstruction and analysis tool chains could enhance the power and reusability of the extensive open-source tools that currently exist in this area.

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