Towards Robust 3D Registration of Non-Invasive Tactile Elasticity Images of Breast Tissue for Cost-Effective Cancer Screening

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***Abstract*— This paper presents current progress on the development of Tactile Imaging, a developing technology for breast cancer screening finding traction in the marketplace, towards non-invasive fully 3D elasticity imaging of the breast. The paper identifies the necessary steps required, and subsequent progress, to develop the technology to image the whole breast robustly which is to be used as a safe screening tool in walk-in clinics. Tactile Imaging has been shown to be capable of binary lesion classification and has seen extensive development, to where benign biopsy rates could be reduced by 23%, but further work is required to make this a clinically practical system for widespread use. Using a hybrid system of Tactile, orientation, and camera sensors it has been demonstrated that robust composite tactile image mosaicking is feasible using the breast vein network as a base map. This paper further outlines the remaining steps needed to turn the current state-of-the-art system from a 2D demonstrator into a fully 3D imaging system that is competitive with other imaging methods, and associated challenges. These being chiefly preparing a phantom reference structure for use in pre-clinical validation, making more stable tactile sensors to reliably perform the new imaging techniques, and building bodies of evidence to build clinical trust in tactile imaging. This work describes that 3D tactile breast imaging is feasible, but that additional work is required to clinically demonstrate these new developments.**

***Clinical Relevance*— This paper presents developments to breast cancer imaging technology gaining clinical traction, developing a new method for rapid breast cancer screening and autonomous reporting to reduce both patient stress and secondary care burden in terms of both time and resources.**

I. Introduction

THE process of Tactile Imaging, also called Mechanical Imaging [1], is a method of elasticity imaging most commonly used for breast cancer screening but has seen increasing academic development to become a self-contained diagnostic tool in the clinical environment [2], [3]. Though many implementations of Tactile Imaging exist, based on mobile piezo-resistive sensing elements [4] or optical hyperspectral imaging [5], the most common in industry and most advanced in terms of academic development is fixed array imaging embodied by SureTouch™ (Sure Inc., US-CA). This technology uses a 12x16 capacitive pressure transducer array to measure the reaction stress from breast tissue at a given level of compression. In doing so, the technology is able to differentiate a breast lesion from the surrounding healthy tissue, as shown in Figure 1, with better accuracy and sensitivity to size and hardness than the clinical breast exam (CBE) and shear wave ultrasound [6] [7], [8]. Currently TI is a commercially available optional screening tool in use in several countries inclusding the US, but current clinical guidelines always require mammography if something suspicious is found.

The key driving force behind the development of tactile imaging to this day is the reduction of patient stress during the process of cancer diagnosis, culminating in reducing the need for uncomfortable and stressful mammography, and eliminating the need for benign biopsies by providing accurate diagnosis of a lesion at the primary care centre or patients home. Additionally, it is important to reduce the skill burden of screening tools so that senior clinical staff can be tasked with more pressing matters.

To achieve this goal and develop Tactile Imaging beyond a simple screening tool, more diagnostic metrics are required than are currently available. This paper details current technological capabilities, before presenting the progress to date on achieving 3D tactile elasticity images of the breast. The key challenges moving forward are presented as goals for future research in this area.

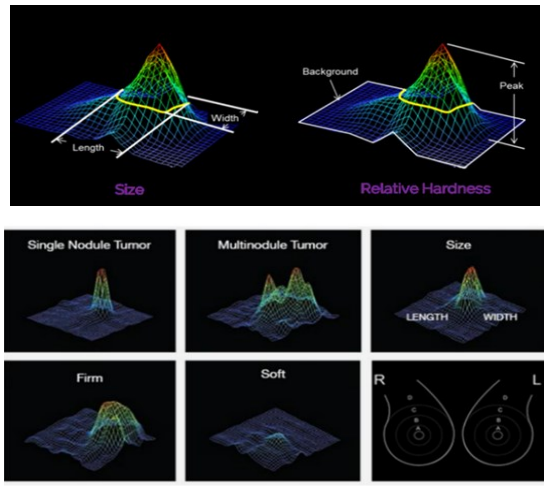

Figure 1 - Examples of Tactile Breast Lesion Images (MyBexa.com)

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II. Problem to be Solved

While mammography is the well established screening tool in countries like the US, UK, and Australia and is unlikely to be shifted due to clinical inertia; in developing nations such as India and China it is not so common and that coupled with higher incidences of breast cancer provide an ample market for a new cost effective noninvasive screening tool [4], [9]–[11]. Benign lesions are far more common than malignant lesions particularly in western countries, so it is important that physicians recognize benign lesions confidently to reduce the need for surgical biopsy [12]. This will reduce the unnecessary surgical biopsy rate, reducing the suffering and rate of complications amongst screening patients.

The primary metrics presented above that are used for clinical diagnostics are: *breast density* [13]*, lesion density and elasticity* [14]*, growth / fluctuation rate, lesion size, shape, and boundary conditions* [15]*, and lesion mobility*. These have been shown to be positive diagnostic metrics from other imaging modalities [16]–[18]. In order for TI to have imaging and diagnostic qualities comparable with that of mammography, the current gold screening standard in many countries, we must be able to image the whole breast and have repeatability between scans for accurate lesion monitoring. This will allow for estimations of lesion boundary conditions, and growth rate that was not possible using TI before. By forming robust 3D images of the breast using TI (or hybrid technology), a solid comparison can be made between scans to allow for measurement of lesion changes and proper reporting to secondary care and oncology if required.

To achieve this, rigid and then nonrigid tactile image mosaicking techniques have been proposed to allow TI to image the whole breast without excessive stress from a viewing the whole breast simultaneously [19].

III. Tactile Image Registration Techniques

A. Tactile Registration using External References

Early iterations of TI mosaicked tactile images together using external magnetic trackers [8], as shown in Figure 2. While this method did work, and provided a method for increasing tactile image resolution by averaging overlapping frames, it was not clinically practicable and so did not progress in the literature. This was due to the tactile image being referenced to an external tracker, which was not able to track patient motion. This meant that the tactile mosaic would lose cohesion if the patient moved during the exam, and so suspicious tissue would be incorrectly reported and positioned in clinical practice.

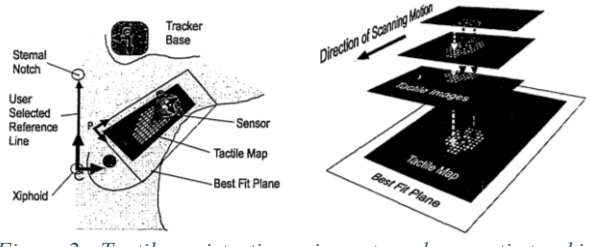

Figure 2 - Tactile registration using external magnetic tracking references [8]. This was highly sensitive to patient motion.

B. Tactile Registration using Tactile Frame Correlation

By 2008, TI was gaining some traction, and at this point commercially available clinical TI still used single frame images of lesions for screening. Image mosaicking using correlation between tactile frames to estimate relative displacement was demonstrated [1] as shown in Figure 3. This provided relative motion between images, but required the scan to follow a known pattern to be registered onto the breast, and so was prone to operator error. Similarly, this method relied on a consistent contact force to maintain correlation between tactile frames, which was difficult to achieve in practice. Due to this, the method was never implemented into commercial units, nor included in clinical validation studies [2], [3]. TI had imaged the whole breast now, like in mammography, but more was needed for clinical robustness.

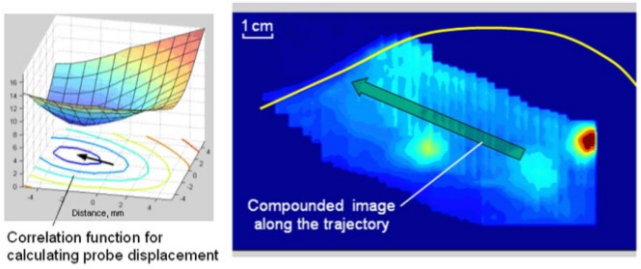

Figure 3 - Tactile registration using image correlation [1]. This was robust to patient motion, but sensitive to operator consistency.

C. Tactile Registration using Inertial Navigation

To combat the reliance on constant load, and to assist in elasticity measurement, a hybrid TI system using inertial measurement was proposed [20]. Here double integration of acceleration (displacement) was used to estimate both compression strain and lateral displacement on the breast to register frames. This was a novel approach, utilizing the inertial sensor already deployed on the TI system for assisting with calibration. The method proved effective at measuring compression displacement and thus elasticity, but was unable to reliably measure lateral displacements due to low acceleration signals and high noise from vibration for this motion type [21]. As the method was not clinically practical, even for elasticity measurements, it was not advanced further.

D. Tactile Registration using Patient Breast References

Robustly solving the tactile image registration problem required referencing the images onto a mobile framework that moves with the patient, so images remain locked to a particular location on the breast. This allows for comparison between subsequent scans as well as properly reporting dimensions and lesion properties. The breast vein structure was shown to be a suitable structure [22], as IR images of the veins were not sensitive to contact load or scan patterns and could be mosaicked relatively simply. By integrating a small IR camera and illuminator into the TI system, a robust tactile mosaic could be created [23] as shown in Figure 4. This had the added benefit of indicating the proximity of lesions to blood vessels; a known predictor of malignancy [24]. This method was demonstrated on 2D phantom materials, but was observed to be resilient to operator variation, and so was deemed a suitable step forward. The method integrated

orientation sensors for use in calibration, which were intended for 3D surface mapping, however this was not implemented.

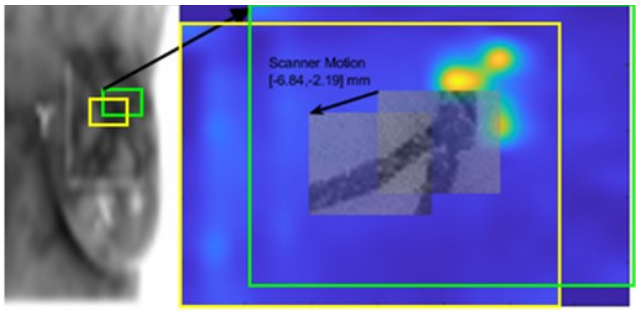

Figure 4 - Tactile registration using patient specific vein structures [23]. This method was robust to patient and operator movement.

IV. Current Project Status

Currently, forming tactile images of the whole breast has been demonstrated on phantoms [23], where advances from previous works [1], [22] were used to translate the composite tactile image into an elasticity image based on knowledge gained from the camera about the background material elasticity, as shown in Figure 5.

This system has been merged into a SureTouch sized unit, demonstrating that the technique can be miniaturized and integrated with currently available commercial breast scanners.

The current system produces a flat 2D image of the breast, as it did before [1], however the system is robust to both patient and operator motion in that the camera can still track the relative motion of the scanner w.r.t. the breast when physical contact is lost. This also applies to rotations as well as translations. This is the major advantage of this system over previous iterations.

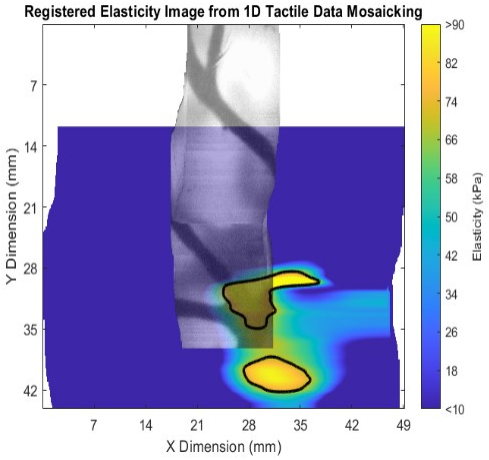

Figure 5 - Integrated tactile elasticity image [23]. Now a robust full breast view is feasible with high spatial resolution.

The second major advantage of the current system over previous iterations is positional repeatability between subsequent scans. Previously, monitoring lesion locations between scans required the operator to repeat the scan exactly as performed initially, which led to frequent errors and for the system to be impractical. With the current system maintaining a vein map of the patient, the scanner can be placed onto an arbitrary area within the scanned area, and imaging matching can be performed on the vein map to identify the current location to reference the next scan. This is believed to reduce the skill requirement for use of the tactile breast imaging system in clinical use, and thus the resource burden

V. Future Plan and Next Steps

1) Demonstrate 3D deformable mosaicking on Phantom

The technical capability to do this is included in demonstrated works [23], where the combination of orientation sensors and tactile sensors allows for the breast surface local normal vector to be determined. Although demonstrated on a planar surface for validation reasons, this will allow images to be mosaicked in 3D space rather than onto a 2D surface, thus producing a 3D tactile view of the breast that can be used for lesion monitoring and robust reporting [25]. This will need to be demonstrated on a 3D tactile phantom with an appropriate vein reference structure visible in 850nm IR.

2) Develop more stable tactile sensors

The screening accuracy of breast TI is well documented [2], [3], where binary decisions are made using basic information about a lesion that is not detrimentally affected by sensor error. Moving forward to sub-class differentiation of lesion types, or detailed characterization of lesion properties, tactile sensor error becomes problematic as shown in other applications of TI [26]. Where absolute measurements are required, for elasticity measurement and characterization of transient properties, the calibration stability of the sensors needs to be improved either through new designs, or algorithmically.

3) Clinically validate development vs previous work

The goal of this whole project is to improve the diagnostic capabilities of clinical TI by improving the robustness and ease of use of the scanner, and by increasing the amount of diagnostic information available such as elasticity and spatial relations of the lesion. These were hypothesized to improve the diagnostic accuracy [2], [27] of breast TI however this has not yet been demonstrated whilst the technology is updated to deliver such information.

In order to do critical clinical evaluation of these new TI techniques, it is necessary to conduct a repeat study of the baseline TI system [2], [3] but with the new technology to ensure that we have comparable sampling and protocol. Once assured, the new techniques can be applied to the clinical data captured to determine the extent of any improvement and to establish whether it is in line with early predictions [2].

VI. Key Challenges Ahead

There are several key challenges that must be addressed to achieve the steps outlined above, in addition to properly performing clinical validation. First and foremost is generating or procuring a suitable breast phantom that has realistic mechanical properties, realistic/representative shape, and a visible vein network for tracking. This would need to be

scanned by a 3D imaging system in order to generate the reference structure to validate proper image mosaicking.

This point presents another challenge, the current system can rectify local breast deformation but cannot deal with shear deformation caused by the whole breast moving. As such the mosaicked image will need to be transformed to the static baseline either by tracking the phantom movement or by applying FEM techniques or physical modelling [28]. Otherwise a method of continuously verifying the phantom surface position using a robotic arm could be used to form the reference surface for measurement validation.

A key challenge is ensuring that clinicians are aware of the technology and its capabilities, and that sufficient evidence exist to warrant use over methods such as mammography and ultrasound. It is similarly important to repeat early studies directly comparing TI to other modalities [7], as the capabilities of other methods have developed too. Continued research in this area helps with both of these issues.

VII. Conclusion

TI has developed to the point where robust tactile mosaicking of the breast is possible, allowing for a full elasticity image of the breast to be generated. Further work in terms of surface profiling and phantom preclinical validation is required to generate fully 3D images from the handheld scanner. Further clinical validation is required to ensure that the developments do in fact improve diagnostic accuracy of TI, and determine how performance compares to contemporary imaging methods such as ultrasound.

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