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Accurate 3D reconstruction of bony surfaces using ultrasonic synthetic aperture techniques for robotic knee arthroplasty

William Kerr[c,*], Philip Rowe[a], Stephen Gareth Pierce[b]

[a] Department of Biomedical Engineering, University of Strathclyde, Glasgow, United Kingdom
[b] Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom
[c] Advanced Forming Research Centre, University of Strathclyde, 85 Inchinnan Drive, Renfrew, PA4 9LJ, United Kingdom

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ABSTRACT

Robotically guided knee arthroplasty systems generally require an individualized, preoperative 3D model of the knee joint. This is typically measured using Computed Tomography (CT) which provides the required accuracy for preoperative surgical intervention planning. Ultrasound imaging presents an attractive alternative to CT, allowing for reductions in cost and the elimination of doses of ionizing radiation, whilst maintaining the accuracy of the 3D model reconstruction of the joint. Traditional phased array ultrasound imaging methods, however, are susceptible to poor resolution and signal to noise ratios (SNR). Alleviating these weaknesses by offering superior focusing power, synthetic aperture methods have been investigated extensively within ultrasonic non-destructive testing. Despite this, they have yet to be fully exploited in medical imaging.

In this paper, the ability of a robotic deployed ultrasound imaging system based on synthetic aperture methods to accurately reconstruct bony surfaces is investigated. Employing the Total Focussing Method (TFM) and the Synthetic Aperture Focussing Technique (SAFT), two samples were imaged which were representative of the bones of the knee joint: a human-shaped, composite distal femur and a bovine distal femur. Data were captured using a 5 MHz, 128 element 1D phased array, which was manipulated around the samples using a robotic positioning system. Three dimensional surface reconstructions were then produced and compared with reference models measured using a precision laser scanner. Mean errors of 0.82 mm and 0.88 mm were obtained for the composite and bovine samples, respectively, thus demonstrating the feasibility of the approach to deliver the sub-millimetre accuracy required for the application.

1. Introduction

Osteoarthritis (OA) is a degenerative disease affecting the articulating joints which causes pain and can eventually lead to a complete loss of mobility in the affected joint (Buckwalter and Mankin, 1997). When symptoms of OA of the knee become disabling, the prescribed solution is knee arthroplasty, which can alleviate pain and increase mobility (Woolhead et al., 2005). While traditional procedures are well established, the bone removal methods are outdated and inaccurate, which can lead to poor alignment and, as a result, poor clinical outcome (Huang et al., 2012). Robotically guided systems can improve cutting accuracy, leading to superior alignment and improved clinical outcome (Choong et al., 2009).

In order to plan and implement procedures using such systems, a preoperative 3D model of the joint is usually required (Roche et al., 2009; Siebert et al., 2002; Cobb et al., 2006; Hananouchi et al., 2008), which is currently achieved using Computed Tomography (CT). While this method is seen as the 'gold standard' in this capacity, it is costly (Fred, 2004) and applies significant doses of ionizing radiation which can contribute to and even cause malignancy (Albert, 2013). Ultrasound imaging could provide a viable alternative to CT in this capacity by offering comparable accuracies, reducing cost and eliminating the risk of ionizing radiation.

Considerable research efforts have been made in ultrasound bone surface imaging for intraoperative registration to preoperative CT models in computer-aided surgery – a brief review of which can be found in (Hacihaliloglu et al., 2014). A smaller number of groups have attempted to employ ultrasound for preopera-

* Corresponding author at: Advanced Forming Research Centre, University of Strathclyde, 85 Inchinnan Drive, Renfrew, PA4 9LJ, United Kingdom.
E-mail addresses: william.kerr@strath.ac.uk, williamkerr69@gmail.com (W. Kerr).

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tive imaging, with most relying on Statistical Shape Models (SSM) to compensate for the sparsity of ultrasound-derived data points (Barratt et al., 2008; Talib et al., 2005; Chan et al., 2004). These models are entirely dependent on *a priori* data in the form of CT training sets. The accuracy of the reconstructions is, therefore, highly dependent on how representative the training set is of the variation of prospective samples (Heimann and Meinzer, 2009). Training sets are often small and include only healthy knee joints which lack the kind of variation in bone shape found in OA sufferers due to bone remodeling (Fleute and Lavall, 1998). These studies did not account for such localized variation, bringing into question the robustness of the use of SSMs in osteoarthritic patients. With this in mind, it would be preferable to reconstruct the surfaces using only patient-specific data.

In addition to employing SSMs, these studies had in common that manually positioned, optically tracked probes were employed. These would have imposed intra- and inter-operator variability in performance and possible line of sight problems (Hüfner et al., 2005). Further to this, traditional B-scan methods were employed universally, which are associated with low resolution and depth-dependent image quality (Guarneri et al., 2015).

Offering improved focusing capability and increased resolution and SNR over more traditional B-scan methods (Holmes et al., 2005), synthetic aperture imaging methods have become commonplace in research in nondestructive testing (NDT). These methods have been employed within biomedical imaging in attempts to increase frame rates through recursive imaging (Nikolov et al., 1999; Jensen et al., 2006) and through decreasing transmissions per image (Chiao et al., 1997).

Reductions in hardware size and cost have also been achieved by use of synthetic aperture techniques for simplification for small scale and hand-held systems (O'Donnell and Thomas, 1992; Karaman et al., 1995). Employment within medical imaging has, however, been relatively limited due to both the inability of most commercial systems to perform Full Matrix Capture (FMC) (a necessity for the Total Focussing Method (TFM)) and the requirement of real time imaging (Jensen et al., 2006). In particular, the techniques have yet to be applied to bone surface imaging, where only traditional B-scan techniques have been considered. Employment in this field could offer the level of accuracy required for preoperative imaging for robotic knee arthroplasty. However, NDT research into synthetic aperture methods has concentrated on the characterization of small defects (Zhang et al., 2013; Hunter et al., 2008; Wilcox et al., 2007), with surface imaging only being performed on simple, continuous surfaces for refractive correction in dual media applications (Mcgilp et al., 2014; Weston et al., 2012). A further challenge in using these methods is that a high number of images would be required to properly represent the entire sample surface, each with accurate positional data.

The ability of a synthetic aperture based ultrasound imaging system to accurately reconstruct complex, bony surfaces is assessed in order to determine the efficacy of using such methods in preoperative imaging for knee arthroplasty. Two samples were inspected: a composite, human-shaped distal femur (which provided accurate shape and scale) and a bovine distal femur (which provided representative acoustic properties and a test of system robustness). Using a 5 MHz, 128 element 1D array, FMCs were captured using an FPGA-based phased array controller, which allowed for high data throughput. The data were processed using both TFM and a form of the Synthetic Aperture Focussing Technique (SAFT) at high rates, achieved by use of a Graphics Processing Unit (GPU) implementation of both algorithms (Dziewierz et al., 2012). These processing methods were employed as they provided different characteristics found at opposing ends of synthetic aperture reconstructions, which allowed for optimisation of the synthetic aperture parameters for the application. Probe manipulation and positional recording were realized using a robotic positioning system. Finally, the 3D, ultrasound-derived surface data were compared with reference models, providing performance levels for the different methods and for the system in general.

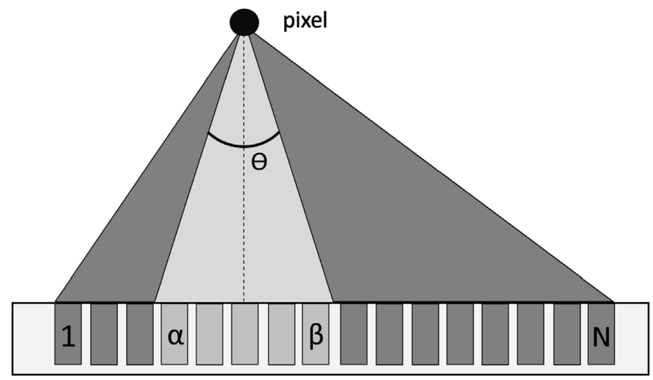

Fig. 1. Comparison of the TFM and SAFT synthetic aperture definitions, with the elements constituting the SAFT aperture shown in a lighter shade.

2. Materials and methods

2.1. Synthetic aperture methods

Both of the techniques employed herein required FMC, which begins by firing the first element of an array and receiving on all. The second element is then fired and reception is carried out on all elements once again. The process is then repeated over all N elements, resulting in an $N \times N$ matrix of A-scans which is collectively known as the full matrix.

It is possible to perform numerous processing techniques with the full matrix in post processing. One possible method is TFM, which synthetically focusses in reception for every pixel in the image using the all the elements in the array. The process begins by discretizing the region of interest into a grid, with each point being equivalent to a pixel in the final scalar image. The intensity of each pixel is calculated as described in (1), in which $S_{i,j}$ is the A-scan associated with a transmission at the ith element and reception at the jth element, while (x, y) are the coordinates of the pixel. The time of travel from the transmitting element to the pixel is $T_{i(x,y)}$, while that from the pixel to the receiving element is $T_{j(x,y)}$. In order to produce a full scalar image, the summation is repeated for every pixel.

$$I(x, y) = \sum_{i,j=1}^{N} S_{i,j}\left(T_{i(x,y)} + T_{j(x,y)}\right) \tag{1}$$

A form of SAFT was also employed in which the same process was performed, but focusing was not carried out on using the full aperture. Instead, the elements constituting the synthetic aperture were defined by the position of the pixel in question. This is shown in Fig. 1, where the SAFT aperture is restricted to those elements contained within an isosceles triangle defined by the angle θ. This is contrasted by the TFM aperture which employs the full aperture. The intensity of a pixel in a SAFT image is, then, given by (2), where α and β are the first and last elements of the aperture, as displayed in Fig. 1.

$$I(x, y) = \sum_{i=1}^{N}\sum_{j=\alpha}^{\beta} S_{i,j}\left(T_{i(x,y)} + T_{j(x,y)}\right) \tag{2}$$

These values vary depending with θ, with an increase in angle effectively increasing the aperture size.