High Resolution Three-Dimensional Ultrasound

Individual Grant Review Report

Background

Freehand 3D ultrasound is acquired by attaching a position sensor to the probe of a conventional 2D diagnostic ultrasound machine. As the clinician moves the probe, its position and orientation is recorded with respect to some fixed datum. The 2D ultrasound images are also recorded. If both the images and the position readings are independently time-stamped then they can be matched up to create a set of 2D slices located in 3D space. Using 3D ultrasound, clinicians have access to visualisation and measurement techniques that are impossible using a normal probe.

Freehand 3D ultrasound has been around since the late 1980s, using a variety of position sensing devices based on magnetic fields, cameras and inverse kinematics. At the start of the project, the Cambridge group had developed one of the best of these systems. The goal of the project was to take a state-of-the-art high resolution 2D ultrasound machine and use it as the basis for a high resolution 3D system. Having built the system, clinical experiments would be performed to assess its utility.

Key Advances and Supporting Methodology

We have constructed a higher definition freehand 3D ultrasound system than anything hitherto reported in the literature, and have published extensive test results to demonstrate its performance [18]. We have developed interactive tools to support a range of clinical applications and pursued speculative engineering investigations resulting in innovative tools and algorithms.

Construction of the high definition system

In previous projects we focused on establishing the correct overall architecture for the freehand 3D ultrasound system. It was therefore possible to develop the high resolution system from our existing system by identifying the principal sources of error, and taking steps to reduce them. Figure 1 shows the dominant errors in freehand 3D ultrasound. The black bullet points show those errors we addressed during the project. Full details of they were dealt with are given in our papers [17, 18, 20]. In this report, we present a general overview of the key issues.

Spatial Calibration. Spatial calibration is required to calculate the position of the B-scan in 3D space using the information from the spatial position sensor. At the start of the project we already had a fast and competitive spatial calibration technique [17]. This was refined by using carefully designed scanning patterns to meet the precision and accuracy requirements of the high definition system [18].

Temporal Calibration. Temporal calibration is required to enable the system to allow for the different delays implicit in the image stream providing the B-scans, and the data stream providing positions. Our existing temporal calibration algorithm was far too inaccurate, producing errors up to 40 ms. A completely new algorithm, designed around modelling and matching smooth probe motion profiles was developed, producing errors less than 5 ms [18].

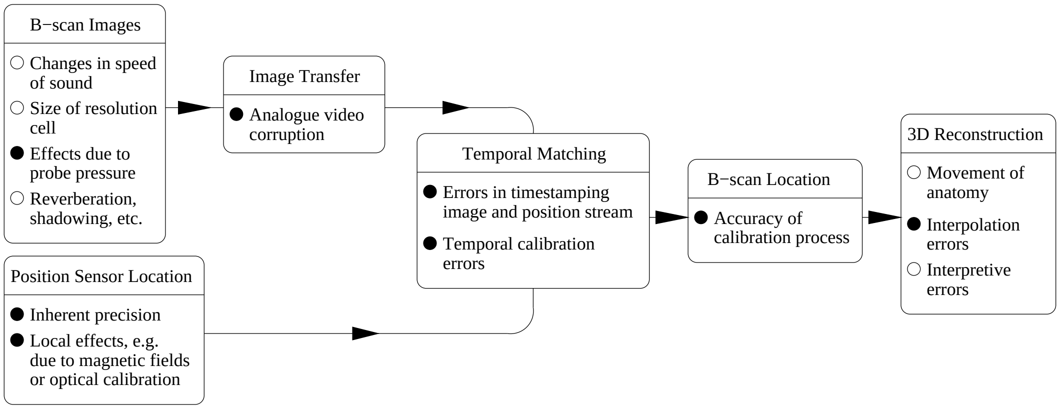
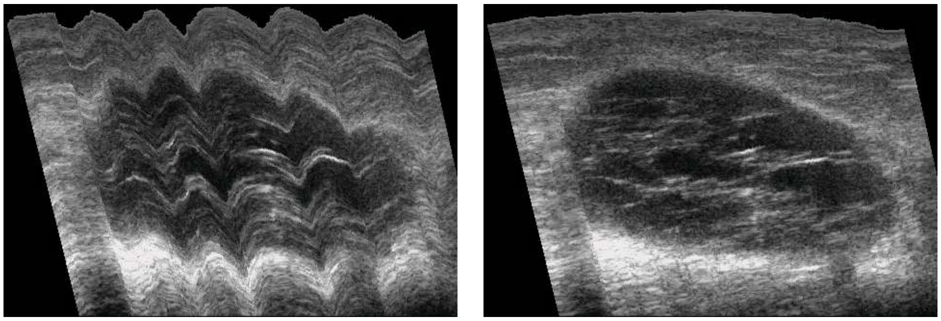


Figure 1: Errors in freehand 3D ultrasound systems. Some of the dominant errors are shown: those with black bullet points have been addressed in the work, those with white bullet points are residual sources of error.

Effects of Probe Pressure. In our early work much of the emphasis was on determining the absolute positions of B-scans as accurately as possible using the position sensor. This is clearly important, but as we used better optical position sensors, and refined our calibration techniques, we discovered that the compression of the tissue due to the tiny contact pressure of the ultrasound probe was a significant source of distortion. If the pixel size is around 0.1 mm then it does not take much force to distort soft tissue by a measurable amount.

We used a hybrid approach to address this problem. The large scale motion was determined by the position sensor, but an image-based technique was used to determine the small scale motion from one B-scan to the next. In order to prevent improper smoothing of the data, image-based motion correction was only applied where it could be related to physically plausible motion or tissue compression. Extensive experiments were performed to demonstrate that the result of the algorithm was genuinely closer to the anatomy being scanned, rather than just smoother [19, 20]. We have found that probe pressure correction is a vital ingredient in all high definition scanning, and we now use it as a matter of course in most of our clinical work. Figure 2 shows the effect of the algorithm on a reslice through a scan of a breast, acquired while the patient was breathing normally.



(a) Original reslice showing the effect of the patient breathing

(b) After probe pressure correction

Figure 2: Scan of a breast, before and after probe pressure correction.

Acquisition of B-scan images. The 3D visualisations and volume measurements performed by Stradx are only as good as the 2D B-scans that the system is able to record. We therefore wished to eliminate the degradation caused by acquiring the B-scan images through an analogue PAL link from the ultrasound machine. This was achieved by transferring the images digitally across 100 Mbit ethernet between the ultrasound machine and the PC running Stradx. Close collaboration with our industrial partners, Dynamic Imaging Ltd, enabled this strategy to be implemented efficiently, and integrated into the Stradx system [18]. As a result of the detailed analysis we were able to perform on the digital B-scans, Dynamic Imaging have been able to make a number of improvements to the firmware DSP algorithms that they use to construct the B-scan images in the Diasus ultrasound machine.

Toward the end of the project (after completing the experiments reported in [18]), we collaborated with Dynamic Imaging Ltd., to develop hardware and software for acquiring the radio-frequency (RF) ultrasound signal directly from the Diasus ultrasound machine in real time. This facility will form a key tool that will be developed further in the scope of our more recent project focused on “Clinically practical freehand 3D ultrasound” (GR/S34366) and in Dr Graham Treece’s Royal Academy of Engineering / EPSRC Fellowship.

Performance of the high definition system. We performed extensive experiments to assess the precision and accuracy of our system. We also converted error measures previously presented in the literature [1, 2, 9, 10, 17] into a form that enabled direct comparison with our own results. This comparison is shown in figure 3, which confirms the high performance of the Stradx system.

Tools to support clinical applications

In previous projects a wide variety of tools were developed to enable planar and non-planar reslicing, segmentation, surface rendering and volume measurement. All of these tools work directly from the primary data, without the need for an intermediate voxel representation. In this project we extended our array of tools, following the same philosophy.

1. *Volume rendering.* There are occasions when the clinician requires a fully 3D view without prior segmentation, and this is normally achieved using volume rendering. We conducted research to find a way to generate an efficient volume rendering, that could be rotated at interactive rates, yet generated directly from the primary data. “Narrow band volume rendering” [5], describes our solution.

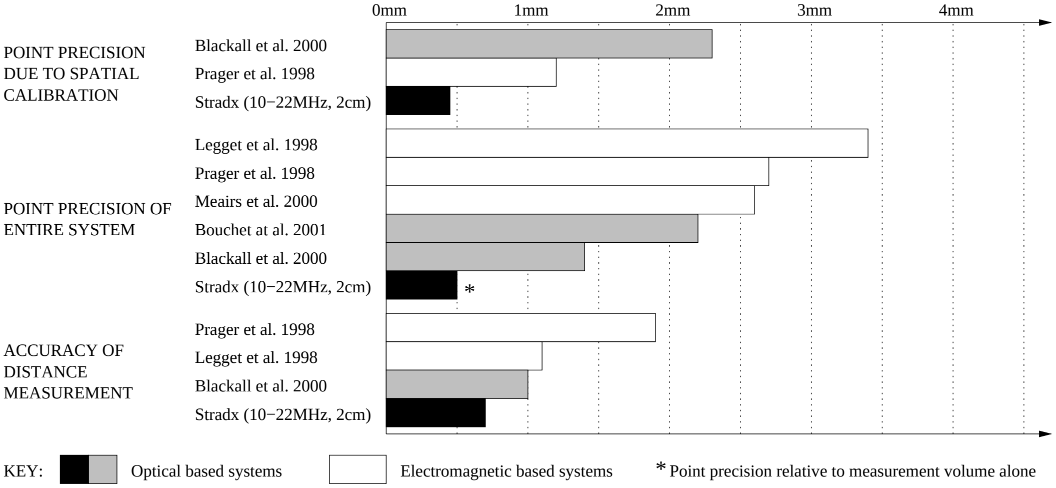


Figure 3: Comparison of the 10-22 MHz Stradx system with other cited freehand 3D ultrasound systems. The bar chart shows the 3D confidence limits for various parameters of the systems. In most cases, this parameter has been estimated from alternative quoted values, as described in [18].

2. *Multi-sweep data.* A key advantage of freehand 3D ultrasound is the ability to acquire data using more than one sweep of the probe. However, even with a perfect position sensor, there will always be small registration errors between adjacent pairs of sweeps because of variations in scanning pressure. Our solution was to first correct any internal inconsistency within the sweeps using the probe pressure correction algorithms described above and then apply an appropriate rigid body-transformation to align the sweeps. This transformation is calculated efficiently by comparing the intersection of both sweeps with a particular plane and is described in more detail in [8].
3. *Scanning pulsating objects.* One of our clinical applications involves acquiring freehand 3D ultrasound data of the carotid artery in the presence of cyclic motion from the pulse. To acquire consistent 3D data of each phase in the cycle we needed to design a gating algorithm. We chose to do this using image-based techniques rather than by introducing an additional input from an electrocardiogram. The result was a flexible and efficient tool that was robust enough to work with grey-scale as well as Doppler data [21].
4. *Fiducial registration* To support our work on breast surgery planning and radiotherapy we have constructed a fiducial registration tool. Using a pointer, we can locate fixed markers in the 3D ultrasound coordinate system and hence register the ultrasound with a X-ray CT scan. The ultrasound is higher resolution than the CT and shows subtle variations in soft tissue much more clearly. Combining data from both modalities and displaying them together considerably enhances the information available for both surgery planning and radiotherapy [22]. For the surgery planning we also integrated the information from the 3D ultrasound scan with a laser scan of the surface of the breast and displayed the result to the surgeon in the operating theatre using a custom designed viewer. This work is described in more detail in the section on Clinical Applications below.

Results of speculative work

We have studied the first and second order statistical properties of the ultrasound speckle signal, concentrating on the size of the resolution cell (beam width), techniques for categorising an image region as coherent or diffuse scattering [3, 12] and algorithms for inverting the non-linear compression mappings applied by ultrasound machines [14].

This work led to a novel algorithm for image based distance measurement based on linear regression of the echo envelope intensity [11, 15]. This provides a new way of measuring the elevational distance between two B-scans. When combined with our in-plane registration algorithms, developed for probe pressure correction, this enabled us to produce a complete prototype system for freehand 3D ultrasound without the need for an explicit position sensor external to the probe [16].

Project Plan Review

The engineering side of the project has been completed substantially according to plan. We have been pleased with the overall performance of the system, the simplicity and elegance of the tools we have designed to support clinical applications and the success of the speculative research into speckle statistics. The collaboration with Dynamic Imaging has been most worthwhile. They have been willing to share detailed design information and source code. As a result, we have made the very best use of their machines and have been able to contribute back helpful suggestions for them to incorporate in future products. We met formally each year with regular contact in between.

The clinical work, described below under 'benefits to society' has also been successful. It was an effective strategy to appoint the clinical research associate one year into the project, when the engineering tools were ready to use. We found it hard to find anyone with appropriate qualifications to take on this post. We also found that the limited availability of suitable patients meant that some of the clinical work took longer than we expected to complete and write up. There were some logistic difficulties associated with maternity leave and (unconnected) time off for a serious operation that our clinical research associate (specialist registrar) had to take. The impact on the project was minimal as a result of the high level of industry and dedication of the person concerned, and indeed of the whole team.

Research Impact and Benefit to Society

Our high definition 3D system has increased the range of imaging applications for which ultrasound is appropriate. This means that more people will be able to have a safe, inexpensive ultrasound scan rather than require CT which involves ionising radiation, or MRI which is very expensive, and therefore limited in availability.

Stradx has been available on the web since 1997. We have produced new features (either as a one-off or as part of our normal six-monthly release programme) in response to requests from research groups in Canada, Finland, Germany and France. We are also in contact with users in Portugal, Hong Kong, China, Italy, the Canary Islands, the Netherlands, Edinburgh, Leeds and London.

Dynamic Imaging Ltd have exhibited our 3D system with their ultrasound machines at trade shows and have gained useful design information as a result of our collaborations on real-time digital image transfer, and radio-frequency data acquisition.

Clinical applications

The goal in the project proposal was to evaluate the high resolution 3D system in the context of three clinical applications. In practice a larger number of applications were explored and from these a number were chosen for continued support.

1. *Use of freehand 3D ultrasound to develop a needle-free injection system.* We were approached by Weston Medical Ltd. who wished to explore whether ultrasound could be used to facilitate the design of their disposable needle-free injection unit. We found that the freehand 3D ultrasound system provided a much clearer indication of the location of the injectate than was possible using MRI imaging, and at a fraction of the cost. The system was used extensively by Weston Medical to facilitate their design process and the scientific results were published in the British Journal of Radiology [4].
2. *Freehand 3D ultrasound in the assessment and follow-up of babies with congenital talipes equinovarus deformity (club foot).* The system is being used to provide information about the arrangement of the (unossified) bones in the foot to facilitate assessment of the severity of the condition and, where appropriate, surgery planning. Figure 4 is a surface rendered image, derived from freehand 3D ultrasound, showing the unossified bones in the foot of a baby with talipes equinovarus. Three dimensional animations based on this data together with geometrical measurements give clinicians a unique insight into the precise misalignments that are present in each case. This work is almost complete and two papers have been submitted to *Radiology* describing it.

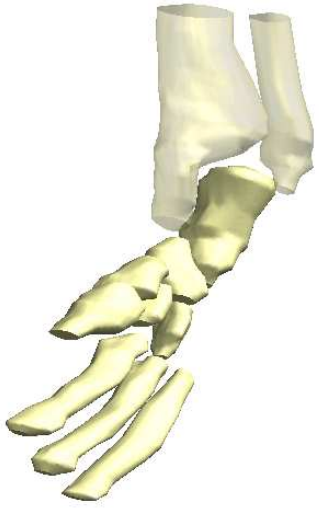


Figure 4: Unossified bones in a talipes equinovarus foot.

3. *Spatial mapping of the brachial plexus.* Accurate knowledge of the anatomy of the brachial plexus is vital to the successful administration of selective anaesthesia in this area. Using high resolution 3D ultrasound we have demonstrated hitherto unsuspected variations in anatomy which explain past problems administering

anaesthetic in this area, and pave the way for safer procedures to be used in the future. Our research registrar, Dr Charlotte Cash, recently won a best paper prize for her presentation on this work at a meeting organised by the European Society of Regional Anaesthesia.

4. *Freehand 3D ultrasound and surface contour mapping to guide breast surgery.* The 3D scan information is combined with laser scan information of the surface to produce a 3D interactive visualisation of the location of the tumour under the skin to aid surgery planning. Ethical approval was granted in December 2003 and preliminary trials are underway involving volunteer patients.
5. *Freehand 3D ultrasound guided breast radiotherapy.* Freehand 3D ultrasound provides useful information about the location of tissue that was close to the tumour before it was excised from the breast. It can be used to improve the accuracy of the radiotherapy-planning CT scan. If the target of the radiotherapy can be located more accurately in this way, then a reduced overall radiation dose can be used, leading to better cosmetic results.

In this list, applications 1, 2 and 3 are substantially complete and publications have appeared or are in preparation. Applications 4 and 5 have resulted in an on-going collaboration which the Cambridge Breast Unit and Department of Oncology are supporting in the hope that it will build into a further project with a strong clinical focus. Other, smaller scale work has been undertaken to explore the use of 3D ultrasound to measure renal transplant volumes, to assess the volume of carotid atheromatous plaque, and to measure the volumes of organs in adolescent survivors of birth prematurity.

Overall, the 3D freehand system appears to offer significant clinical benefits when one or more of the following three conditions apply:

- when the structure of interest is too big to fit into a single sweep of an ultrasound probe,
- when it is necessary to register the 3D ultrasound accurately with a fixed external coordinate system and
- when a 3D scan is required using a specialist (eg. high frequency) ultrasound probe.

Expenditure

The only major unexpected expenditure was the cost of the maternity leave salary for the clinical research associate. Permission was sought from the EPSRC and the cost has been included in the accounts as an additional exceptional item. On 15 September 2003, Dr Richard Prager presented a poster at the EPSRC theme day in Bath and claimed £112.60 expenses.

This grant has enabled the Cambridge Medical Imaging group to achieve an internationally leading position in high definition freehand three-dimensional ultrasound imaging. This position will be developed in the future as a result of the following additional funding:

- An EPSRC grant focused on “Clinically practical freehand 3D ultrasound” (GR/S34366).
- An Royal Academy of Engineering / EPSRC five-year Fellowship awarded to Dr Graham Treece to work on the mitigation of artifacts in 3D ultrasound.
- An allocation of £81700 out of the University of Cambridge’s SRIF II budget to equip a mechanically-swept radio-frequency three-dimensional ultrasound imaging facility in the Engineering Department.
- A sabbatical from teaching and administration for Dr Richard Prager to spend the academic year 2003–2004 on ultrasound research.

Further Research and Dissemination Activities

Future research will focus on techniques for extending the application domain of ultrasonic imaging, and making it easier for clinicians to use. We have recently demonstrated, we believe, the first ever freehand ultrasonic elastography system; we are working on ways to combine volumetric probes with freehand scanning systems and techniques for acquiring freehand data without an external position sensor. In the longer term we will use our expertise in radio-frequency ultrasound to develop techniques to characterise material properties and acquire images at resolutions smaller than the ultrasound wavelength.

All the research undertaken during the project has been published in peer-refereed journals. We have also been invited to write descriptions of our system for *Pattern Recognition Letters* [6], *Ultrasonics* [13] and the *British Journal of Radiology* [7]. Each year since 2002 we have given an invited presentation on the Stradx system at the Euroson school on 3D Ultrasound Imaging organised by Imperial College Faculty of Medicine in association with the British Medical Ultrasound Society.

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