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High Definition Ultrasound Imaging for Battlefield Medical Applications†

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Abstract

A team consisting of Sandia National Laboratories (SNL), University of Texas Health Science Center at San Antonio (UTHSCSA), and an industry partner has developed technology that improves ultrasound definition. This development is in the second phase of an evolutionary process that will eventually provide a system for general diagnostic applications. Although our sponsored work has been focused on portable, low-cost, military diagnostic applications, other obvious beneficiaries would be urban and rural hospitals, clinics, and private physicians' offices. Because of the advantages of portability and non-ionizing radiation, the military can apply this ultrasound imaging modality in a remote critical care pod to diagnose wounds in injured soldiers as they would with any medical diagnostic imaging system.

In this paper, we describe the development of an ultrasound based imaging system capable of generating 3D images showing surface and subsurface tissue and bone structures. We have included results of a comparative study between images obtained from X-Ray Computed Tomography (CT) and ultrasound. We found that the quality of ultrasound images compares favorably with those from CT. Volumetric and surface data extracted from these images were within 7% of the range between ultrasound and CT scans. We have also included images of porcine abdominal scans from two different sets of animal trials.

Introduction

The research and development described in this paper will enable 3D ultrasound imaging to replace and/or supplement more expensive and higher risk non-intrusive imaging techniques such as Magnetic Resonance Imaging (MRI) and CT. This advance is of particular importance to the Department of Defense because 3D ultrasound is simpler, safer, and less expensive to use in battlefield conditions. Also, with regard to wound penetration, 3D ultrasound can provide both geometric anatomy and Doppler blood-flow information which will allow the medic to triage the patient more quickly and accurately. Additionally, this work will benefit the civilian medical community by reducing the risk of excessive radiation exposure and by lowering the cost of U.S. health care.

This paper provides an overview of a low-cost, portable, 3D ultrasound imaging system that could be used in military or civilian medical applications. It begins with a problem statement, a discussion of our approach, a brief assessment of prior work, and a review of our research. The paper then describes our developmental system and the immediate goals of the research project. That section is followed by a discussion of the major findings using the developmental system, then by a discussion of the calibration procedure. The latest improvements to the hardware system were presented next followed by a description of the data reconstruction procedure. The latest results of the animal trials are presented in the Results and Discussion section. This section is followed by a discussion of the recommended work for the future.

Problem

Battlefield medical staff currently lack the ability to acquire diagnostic images of wounded soldiers to determine the extent of their injuries. The technology that would provide portable, fast, and safe diagnostic imaging necessary for a critical care pod is not available presently. In far-forward battlefield scenarios, wounded soldiers must be treated within the first hour to stop their bleeding after injury. This hour is referred to as the "golden hour." Diagnostic imaging plays an important role in determining the extent of injury and, subsequently, in stopping the bleeding. Broken bones, bone fragments, shrapnel location, and tissue damage must be identified quickly using portable, fast, and safe diagnostic methods so that surgeons can remove the fragments and/or stop the bleeding.

Current imaging modalities such as X-Ray and MRI are limited because of their large size, ionizing radiation (for X-Ray), and expense. Typical X-Ray CT and MRI machines are designed to be enclosed in large rooms with substantial shielding to protect people outside the rooms from harmful effects. These devices can cost several million dollars to purchase for use in hospitals. Although portable CT devices have been developed for various applications, the ill-affects of harmful radiation can be limiting [1].

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Further problems occur with blood and open wounds when imaging requires sterile conditions. Also, problems occur with current commercial ultrasound units because images are not intuitive.

Approach

The results from the scanning platform developed in our earlier 3D prosthesis work have confirmed the model predictions as applied to prosthesis fabrication [2]. From this work, which focused on developing an anatomical database from an amputee's residual limb for automated prosthesis fabrications, image definition was substantially improved beyond standard off-the-shelf ultrasound. This development led us to pursue our current work in high definition ultrasound for diagnostic purposes.

A key feature behind the philosophy of our development has been to provide precision orientation and positioning of the ultrasound probe as well as data fusion of the recorded images based on Synthetic Aperture Radar (SAR) and Advanced Target Recognition (ATR) technologies.

While several other researchers [3] [4] are currently developing technology to support marketing 2D array transducers with the goal of real-time 3D ultrasound imaging, our concern has been based on the knowledge that 1D and 2D array transducers, no matter how sophisticated, suffer limitations in providing high definition signal to noise ratios uniformly within a single image frame. Those limitations are caused by the specular nature of reflective mode ultrasound.

One of the most useful features of ultrasound is its ability to scan and formulate a composite "mental" image of the anatomy based on a series of ultrasound images formed while continuously moving, aiming, and optimizing the image. Most ultrasound machines have recognized this benefit and have provided cine-loop features to replay sequences for clinicians. In this way, repetitive observation of a sequence of images allows the clinician to form a mental 3D solid rendering of the image.

Our approach takes advantage of this method of image formation and creates a composite image based on precision motion and characteristics of the image derived from the system. While the authors recognize the benefits of eventual real-time 3D ultrasound imaging that is currently the focus of much research, it is also important to remember some of the harshest criticism of ultrasound imaging surrounds the image quality and non-intuitive format of all current systems.

Unlike CT or MRI, where natural landmarks are easily provided and recognized in cross-section, ultrasound cross-sectional images are unregistered by familiar forms or landmarks, and that fact limits its use to those who are fully trained in the art of recognition. It is important to observe that most clinicians formulate landmarks by moving the probe over familiar anatomy to obtain reference points.

Finally, ultrasound imaging continues to rely on motion to develop a full understanding of the anatomy under study. Consistent with our philosophy of ultrasound use, our research recognizes this inherent necessity and incorporates the benefits of motion with the additional improvements of intuitive format and high definition. This method optimizes ultrasound images on a pixel level.

It is clear that both 2D and 3D real-time ultrasound imaging can be used as the basis for our approach. The benefits of 3D over 2D imaging occur in reducing the time required for image formation, as well as in improving image quality. Theoretically, a multi-dimensional ultrasound array can form and aim the beam in a way that would eliminate the need for precision motion of the transducer. Such an array would need to be extremely large in order to encompass the entirety of an anatomical feature such as a leg, arm, abdomen, or thorax, and to completely optimize the image on a pixel level as our system can provide. The system would also need to be calibrated to allow for precise image reconstruction. Taking into consideration the relative costs and benefits of each approach, it seems likely that the ultimate configuration will be a combination of multi-dimensional arrays, precision motion, and image reconstruction in order to form the highest definition ultrasound images possible at the pixel level.

Initial Work

Substantial work has been done in the area of 3D ultrasound imaging. The need for better fitting prostheses has driven the early work in the area of 3D ultrasound imaging. Nelson in 1993 described work in 3D ultrasound imaging with emphasis on visualization [5]. His images, however, are limited in clarity and definition. Sakas in 1994 reported techniques to improve the image quality and methods used to perform volume rendering and surface extraction [6]. Hamper evaluated applications of three-dimensional ultrasound in a clinical setting in 1994 [7]. The Sandia/UTHSCSA team has generated high quality ultrasound leg images because of our methods of maximizing the signal strength in combination with novel noise suppression algorithms. Sandia's image quality is comparable to CT or MRI images in terms of clarity and definition.

The original Sandia/UTHSCSA work focused on the accuracy of the image data as it was applied to producing better fitting prostheses. There are over a half million amputees in the United States to date. Additionally, nearly 60,000 leg amputations occur each year. Worldwide, the number of amputations that will result from mine injuries is not countable. Current manual techniques used in the fabrication of prosthetic limbs are not sufficient to provide limbs that fit properly at a low cost to patients. For example, in the

United States, each artificial leg can cost from $3,000 to $15,000. A typical patient can expect to need two to five different prostheses in the first few years following amputation, owing to limb atrophy, or, in the case of children, limb growth. Lack of an accurate low-cost method for obtaining accurate skin and bone surface definition is a primary cause for high cost prostheses. Information on tissue and bone locations as they interface with a prosthesis is essential to determining weight distribution, prevention of pressure sores, and, ultimately, patient comfort.

The 3D ultrasound imaging system developed at SNL in collaboration with UTHSCSA consists of an off-the-shelf ultrasound image capturing machine, custom hardware, and control and image processing software. Figure 1 shows the mechanical scanner portion of the custom hardware that has an adjustable orientation transducer. The tank and transducer are rotated around the leg generating a series of 2D slices. These 2D slices are later combined to generate a complete image section.

The Sandia/UTHSCSA system takes advantage of the highest quality ultrasound that was available on the market at the time we purchased the machine. By moving the transducer as we developed the image, we optimized the image. We reoriented the transducer to match the specular surface to follow the contours of the anatomy. The goal was to optimize the image on a pixel level in order to provide the highest definition possible throughout the entire frame. Substantial technologies were borrowed from SAR/ATR. A clinical trial was performed to compare our ultrasound images to the "gold standard" of CT [8].
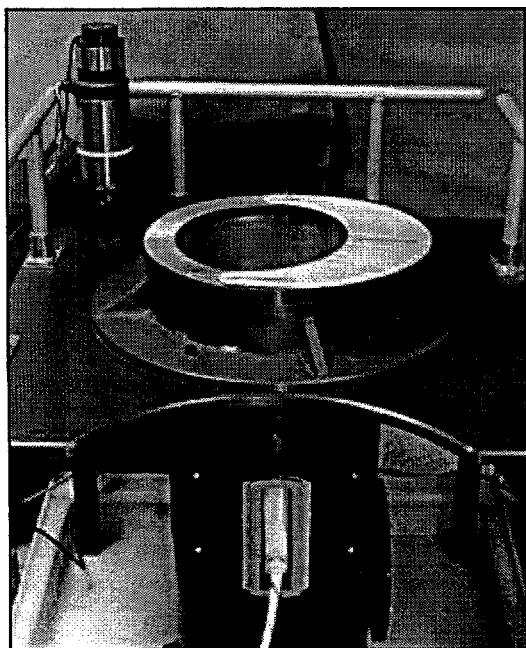

Fig. 1 Scanner with transducer

Image quality results of approximately 93% matching in skin and bone surface comparisons were obtained

[8]. Figure 2 shows an ultrasound cross-section and Figure 3 shows an X-Ray CT cross-section of a leg. The ultrasound image depicts clearly the anatomy of the leg, in that, the tibia, fibula, gastrocnemius, soleus, interosseous membrane, myofascial planes are clearly identifiable. The CT image provides less distinction on muscle fascial planes, muscle/fat interfaces, and blood vessel definition compared to the ultrasound image. These results prompted us to pursue phase 2 research applying the technology to diagnostic imaging. The focus of our current work is on formation of the 3D image, improved display, and additional clinical trials for comparison to CT.
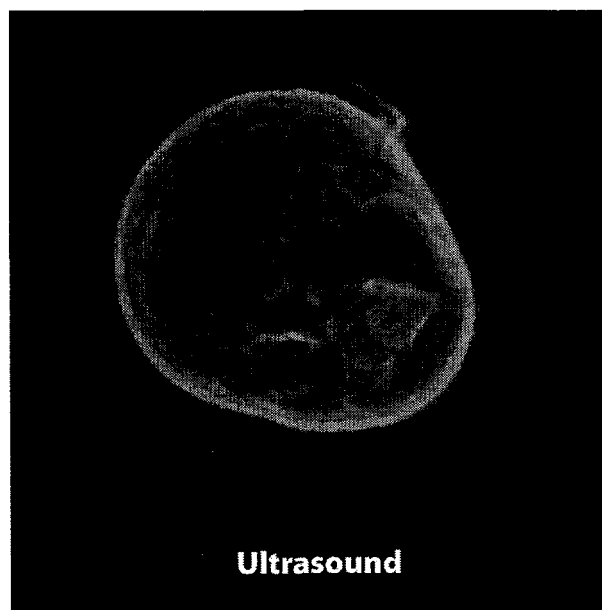

Ultrasound
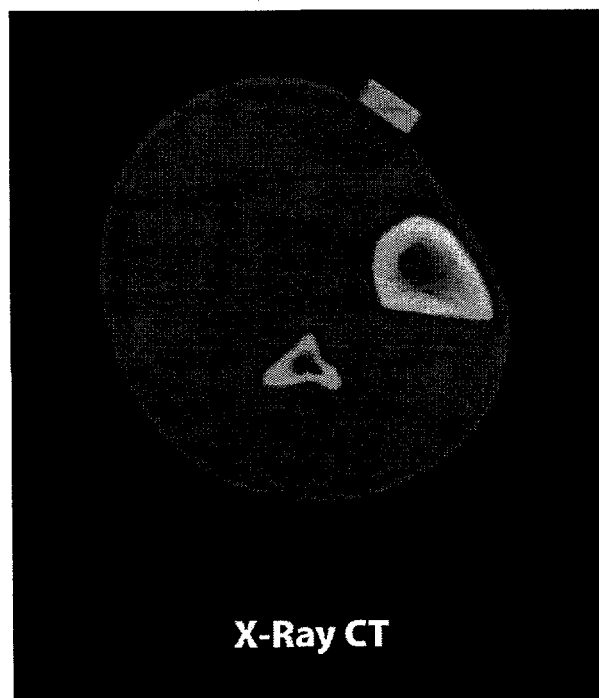
Fig. 2 Ultrasound image of a leg.

X-Ray CT

Fig. 3 X-Ray CT image of a leg.

The 3D ultrasound imaging system was tested on 9 unilateral below-the-knee amputees at UTHSCSA. Image data was acquired from both the sound limb and the residual limb. The imaging system was operated in both volumetric and planar formats. An X-Ray CT scan was performed on each amputee for comparison. Qualitative and quantitative studies were performed to compare CT and ultrasound data sets. Results of the test indicate beneficial use of ultrasound to generate databases for fabrication of prostheses at a lower cost and with better initial fit as compared to manually fabricated prostheses. In addition, qualitative results indicate that planar images represent substantial improvements over standard single-frame ultrasound images and that they could serve as improved diagnostic images.

As part of the program, a computer implemented, first order model of the ultrasonic imaging system was developed. The model essentially computes a geometric (ultrasonic) optics image of a transverse section of the leg that assumes a homogeneous tissue material with imbedded bone structure. The image predicted by the model includes effects of refraction, attenuation, acoustic impedance variations, and velocity errors. The model also includes an empirical approximation of the effects of the transducer beam divergence. Primary applications of the model include the evaluation of concepts before incorporation into experiments and designs, the illustration of the general character of the image, errors caused by refraction, and variations in acoustic velocity in tissue and the coupling medium.

The specular character of the bone image is illustrated by the model computation shown in Fig. 4. In the figure, the solid lines show the bone and skin surfaces, and the small squares show the computed image of the corresponding bone and skin surfaces.
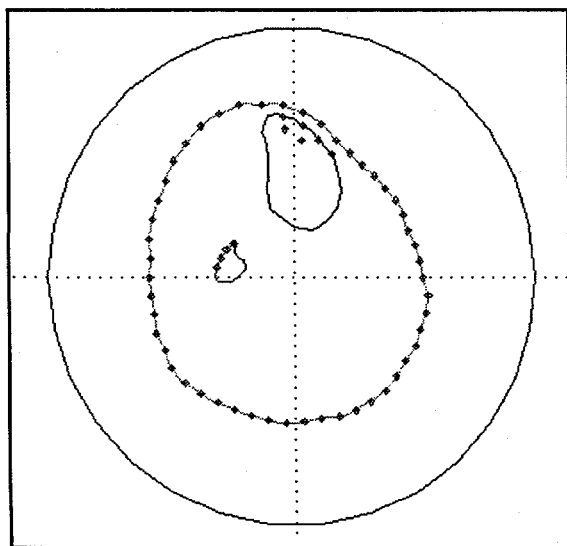

Fig. 4 Specular character of bone image

It can be readily seen from the image that only the part of the bone surface approximately normal to the incident ultrasonic radiation will be imaged by the system. If needed, the portion of the bone that is imaged can be increased by designing a scan pattern that tracks the bone surface normal. Another major problem occurs in the cluttered nature of the image. That is, there will generally be difficulty in distinguishing the bone surface from the images of the various soft tissue differences throughout the leg. This problem will be attacked using a combination of system design and image processing. Further, the image/signal processing will determine the accuracy of the extracted 3D image of the bone and skin surfaces.

Calibration

System calibration can be broken into two parts--image formation and image reconstruction. In terms of image formation the beam width and speed of sound in non-homogenous materials have a major affect on image accuracy. A multi-target phantom was used to determine the image accuracy of the ultrasound machine. With focal zones set throughout the image and gains set to optimize the image, a rectangular pattern 80 mm wide by 90 mm deep was measured using the ultrasound machine. In the image, 0.3 mm diameter pins appear as a 1 mm deep by 3 mm wide in the near field and 1 mm deep by 7 mm wide in the far field. Furthermore, image depth was shorter by 1% (0.8 mm shorter over the 80 mm depth) and wider by 3% (3 mm longer over 90 mm width). Measurements were made on images to determine the image point spread function as shown in Figure 5.

In these experiments, wires were placed at varying distances from the probe and oriented longitudinally along the array. Image intensity was observed to be strongest in mid-field (midway between zero and maximum on depth) and beam width diverged on either side of the focal zone as would be expected. Multiple echo artifacts appear in phantom images but do not appear in human leg images. This effect may be caused by greater reflectance at the phantom/water interface.

Several factors influence image reconstruction accuracy. A rotation matrix is applied to each individual 2D slice to regenerate the image. An offset is applied to each slice to obtain the correct radial distancing. In order to determine accurate radial distancing, a wire was placed at the center of the scanning tank and the tank was leveled. Images were then gathered on the wire and the image reconstruction algorithms applied. A dot in the middle of the tank of "appropriate size" was used as an indication that the correct offset was applied. Adjustments provided by the transducer bracket allowed for adjustments in pitch and yaw orientation so that small alignment adjustments could be made.
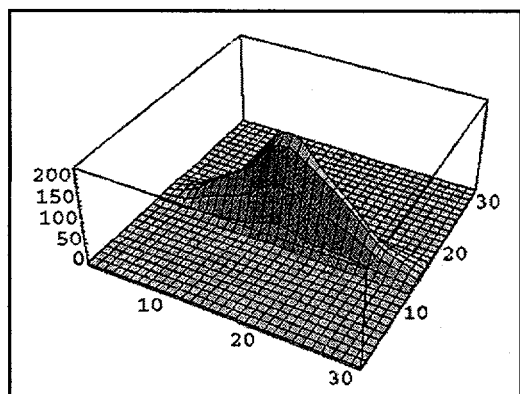
Fig. 5 Image point spread function

System Hardware Improvements

Since the original system allowed for motion in only a single axis (on the azimuth, in a horizontal plane), the next logical step was to accurately maneuver the transducer vertically. This additional axis allows for the generation of multiple 2D cross sections for 3D reconstructions. The current hardware on the floor solves this problem by creating two degrees of freedom for this type of data gathering. VME motion control and image acquisition boards exist along with a real-time controller to accurately position the transducer and acquire images from the ultrasound. Because the ultrasound frame update ratio is a function of chosen parameters like focal zones and output gain, a synch signal is brought out of the ultrasound machine that signifies when the video information has been updated. This signal links positional information from the motor encoders with video information from the ultrasound. A custom graphical user interface running on a Sun computer serves as the system supervisor. Here, the operator can set several parameters for system operation.

Image Reconstruction

In the horizontal scanning mode, individual frames are acquired at a predetermined angular increment about the limb, as depicted in Figure 6. A cross-sectional reconstruction process is then applied which involves angular rotations, motion compensation, and the filtering of rank values, resulting in a highly defined planar cross section of the limb
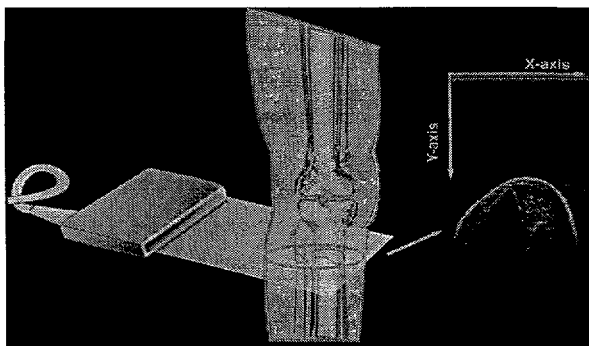

Fig. 6 Horizontal reconstruction

In the vertical scanning mode, the transducer is oriented parallel to the vertical axis of the tank. Individual scans are acquired at a predetermined angular increment about the limb, as seen in Figure 7.
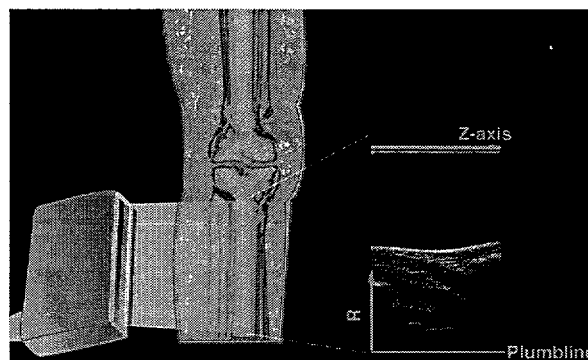

Fig. 7 Vertical reconstruction

A reconstruction process is then applied which uses angular rotations and polar interpolation resulting in a volumetric reconstruction. The software developed to process ultrasonic images has been integrated into the joint Sandia/University of New Mexico system [8], which is an environment that explores algorithmic development and image processing. It uses industry standard routines for basic image conversion, processing, and display. Application-specific routines can also be integrated into the system. These routines may contain calls to standard software library functions, or user-written library functions that add variations to the system.

Results and Discussion

We have performed two series of porcine abdominal scans in which over 5000 images were collected to form cross-sections. Two pigs weighing approximately 40 pounds each were used in these two series of animal trials. Neither one of the pigs was sacrificed and both were under total anesthesia throughout the procedure. The abdominal skin area of the pigs was shaved to remove the hair. The temperature of the water in the tank was kept at near 100°F so as to eliminate hypothermia to the animal. The lower body of the animal was taped and a jacket was used to support the upper body, thereby allowing the pig to be suspended vertically in the tank. The animal was held stationary in the tank while the transducer was spun around to collect 64 to 100 single-frame images to form a cross-section. The scan time was about 18 seconds for a 360 degree scan.

Thirty sets of scans were collected in the first animal trial. However, many of these scans showed excessive motion that was beyond the effective range of our motion compensation algorithm. The pig was allowed to breath freely in the first animal trial. The excess motion was caused by both the breathing of the animal and inadequate restraint between the posteria and the turntable on which the pig was supported during the scan. Both of these factors were improved for the second animal trial. Figure 8 shows a composite cross-

section of the lower abdominal region taken below the rib cage during the first animal trial. Notice that the gain on the ultrasound machine was set high so as to provide better image contrast.

Twenty four sets of scans were collected in the second animal trial. This time the pig was connected to a ventilator which hyperventilated it just prior to the scan. Breathing was then stopped during the 18 seconds when the sensor rotated around to gather the single-frame images. Additionally, the support for the pig on the turntable at the bottom of the tank was improved to stabilize it when the sensor was in motion. These devices eliminated the excess motion and greatly improved the quality of the images. Figure 9 shows a composite cross-section taken during the second animal trial.

In both Figures 8 and 9, the vertebra, psoas, muscles, vertebral muscles, intestines, and genitalia can be clearly seen. There are regions in the intestinal tract where air limited the penetration of the ultrasound in both images. The higher gain setting in Figure 8 shows the spinal cord region clearly with a higher contrast image. However, the high gain setting did cause artifacts to form near the central region of the image. We attempted to reduce some of these artifacts by decreasing the gain setting in the second animal trial.
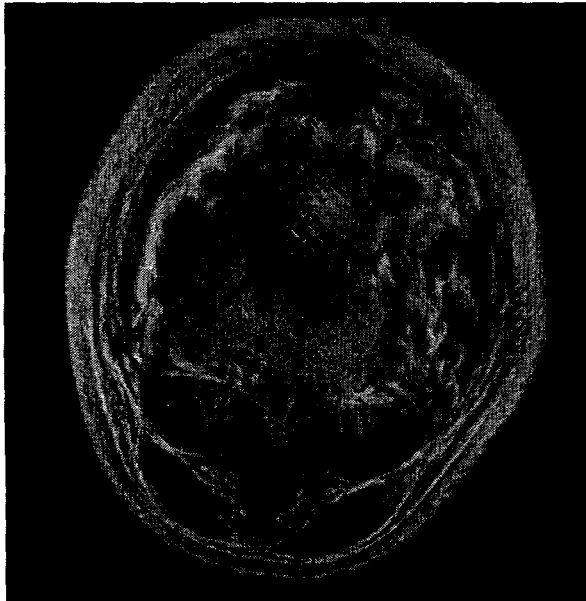

Fig. 8 Porcine abdominal cross-section with high gain setting.

Figure 9 shows a composite cross-section of the lower abdominal region. The abdominal wall, intestine, spinal cord and the surrounding four muscle groups, kidneys, as well as the reproductive organ are clearly identifiable.
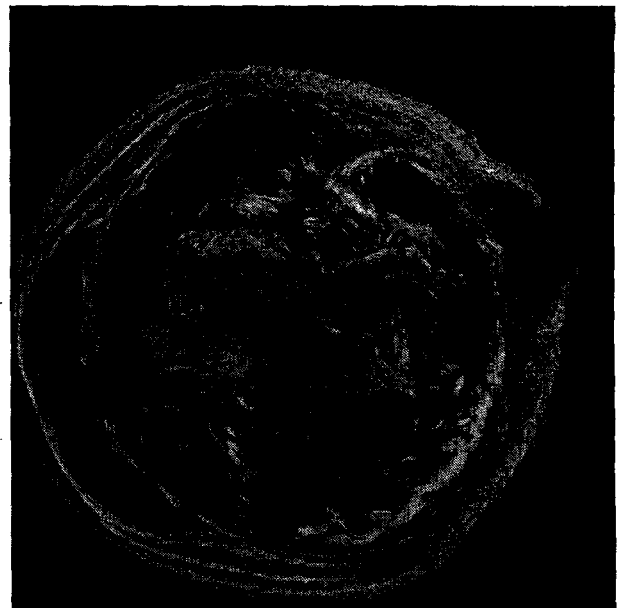

Fig. 9   Porcine Abdominal Cross-section with Low Gain Setting.

These preliminary results provide evidence that ultrasound could be used to image the abdominal cavity of the patient/soldier and provide diagnostic benefit. With doppler applied in future work, blood flow in critical vessels such as the aorta, vena cava, and limb arteries could be quantified to detect for bleeding.

This experimental imaging system produces high quality ultrasound images that are comparable to X-Ray CT images by combining precise robotic positioning with image processing techniques. An example comparing an ultrasound image to an X-Ray CT image is shown in Figure 10. The ultrasound image was generated using Sandia's unique redundant imaging technology.
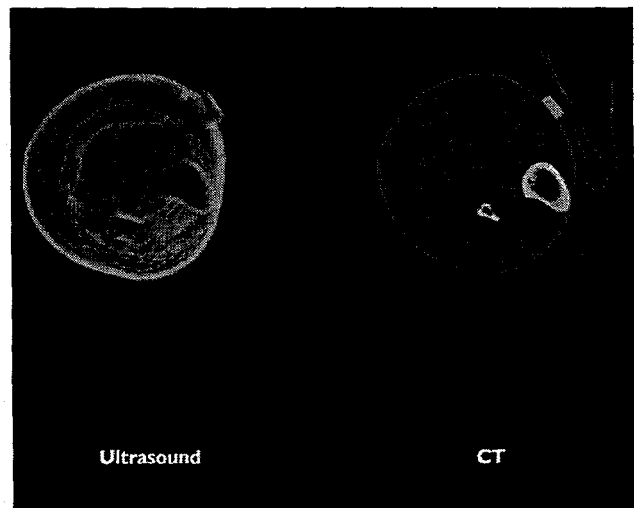

Ultrasound   CT

Fig. 10 Ultrasound image compared with CT image

To date, competing technologies in 3D ultrasound imaging have been limited in their results because there

has not been an effort to precisely control the position and orientation of the transducer. The resulting images from such systems contain substantial noise and clutter common to standard ultrasound images. It should be noted that imaging modalities such as X-Ray, CT, and MRI take advantage of precise position and orientation control in order to provide high quality imaging. The same benefits can be provided with ultrasound.

The system described in this paper is suitable for battlefield applications and is a direct result of the technology and knowledge base that has been generated in 3D ultrasound over the past four years, as well as years of technology development in synthetic aperture radar, atmospheric turbulence phase aberration correction, robotics, and motion control that have enabled our successful efforts of the past. The system will allow research in the field of 3D ultrasound imaging to progress beyond the currently limited configuration of a water tank into the realm of general purpose imaging.

Future Work
The goal of our future efforts is to move toward a more general purpose system that would allow us to combine ongoing developments in commercial ultrasound technology with features that are only provided by our system. With this approach, it is possible to achieve the best of both off-the-shelf technology and innovative technology evolved during the project, while not being limited to a particular company or product. As improvements in commercial systems are released, they can be integrated with our system. The end result will be the highest level of performance without competition with commercial companies, while preserving our dedication to excellence.

Relative to forward echelon support in battlefield applications, the quality of the image can be improved by using a precise medic-assisted positioning robotic device to generate redundant ultrasound data, and then processing that data with enhanced adaptive acoustic and image processing algorithms. The benefit of this approach is a robotically based system that is NOT dependent on any particular ultrasound hardware and that can be used with any number of systems. The overall system can be divided into two parts:
    1) The ultrasound imaging system that is provided by the commercial ultrasound partner, and
    2) The robotic, positioning system provided by Sandia that integrates the image capturing, reconstruction, processing, and phase aberration correction subsystems.

Ultrasound companies working with Sandia will provide planar and 3D array technologies that will be integrated within the same platform. Array technologies by themselves cannot provide the flexibility in controlled positioning over the wide range of angular sectors that can be provided by a robot arm. Using the improved ultrasound system as proposed, a medic can manually scan a body while the robotic

system maintains the trajectory to optimize the image by redundant imaging.

Moreover, similar to CT and MRI, homogeneous high definition ultrasound can only be achieved by optimizing the image on a pixel level. In order to achieve this goal, motion is critical. Motion provides optimization of specular image formation that is inherent in reflective mode ultrasound. Motion also provides for imaging of large anatomical regions without the cost of large ultrasound arrays. The ultimate system design may eventually be a combination of 2D arrays and motion, and may eventually approach the utility, high definition, and intuitive formats of CT and MRI without the problems of ionizing radiation, high cost, and limitations of portability.

Conclusions
We have described the technology developed as a result of our research that will enable 3D ultrasound imaging to replace and/or supplement more expensive and higher risk non-intrusive imaging techniques such as MRI and CT. This work is of particular importance to the Department of Defense because 3D ultrasound is simpler, safer, and less expensive to use in battlefield conditions. Also, with regard to wound penetration, 3D ultrasound can provide both geometric anatomy and Doppler blood-flow information which will allow the medic to triage the patient more quickly and accurately. Additionally, this work will benefit the civilian medical community by reducing the risk of excessive radiation exposure and by lowering the cost of U.S. health care.

A laboratory prototype imaging system has been built to aid in the development of an ultrasonic imaging system to generate three-dimensional mapping of skin and bone surfaces needed for computer aided design of prosthetic limbs. The laboratory system incorporates a commercial ultrasonic imaging transducer. Our latest results provide evidence that ultrasound could be used to image the abdominal cavity of the patient/soldier and provide diagnostic benefit. With doppler applied in future work, blood flow in critical vessels such as the aorta, vena cava, and limb arteries could be quantified to detect for bleeding.

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Biography

Kwan S. Kwok is a Senior Member of the Technical Staff at Sandia National Laboratories. He serves as the Principal Investigator for the 3D Ultrasound Imaging for Portable, Low-cost Diagnostics and Anatomical Geometry Definition project. He has over 18 years of experience in nuclear engineering, space nuclear systems, dynamics and controls, and robotics. He holds a PhD and an SM in nuclear engineering, and an SB in mechanical engineering, all from the Massachusetts Institute of Technology. Dr. Kwok is currently a project manager and principal investigator in the Intelligent Systems and Robotics Center.

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