International Congress Series 1230 (2001) 190–196

An ultrasonic volumetric scanner for image-guided surgery

Jeremy Johnson[a,b,*], Ömer Oralkan[b], Kambiz Kaviani[b], Utkan Demirci[b], Mustafa Karaman[b], Pierre Khuri-Yakub[b]

[a] *Image Guidance Laboratory, Department of Neurosurgery, Stanford University School of Medicine, 300 Pasteur Rd., S-008, Stanford, CA 94305-5327, USA*
[b] *Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305-4085, USA*

Abstract

The design of a two-dimensional ultrasonic array for providing real-time volumetric imaging during minimally invasive surgery is presented. The array is fully populated with capacitive micromachined ultrasonic transducers. A custom-designed experimental system is used to capture A-scans from the transducers. Pulse-echo images from a 16-element 1D array have been constructed. Point spread functions have been simulated for both 1D and 2D arrays. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Three-dimensional ultrasound; Capacitive micromachined ultrasonic transducer; Two-dimensional array; Subarray processing; Ultrasonic imaging

1. Introduction

In this study, a real-time ultrasonic volumetric imager employing capacitive micromachined ultrasonic transducers (cMUT) is explored for image-guided surgery. A common method for image-guided intervention is frameless stereotactic surgery. With this method, preoperative volumetric images, typically obtained via magnetic resonance (MR) or computed tomography, are acquired prior to surgery and registered to the patient at the beginning of the surgery. The position and orientation of surgical instruments are tracked throughout the surgery and overlaid on the preoperative volume image set [1].

* Corresponding author. Department of Electrical Engineering, Stanford University, 450 Via Palou, Box N-108, Stanford, CA 94305-4085, USA. Tel.: +1-650-723-0695; fax: +1-650-725-2533.
E-mail address: jeremyj@stanford.edu (J. Johnson).

0531-5131/01/$ – see front matter © 2001 Elsevier Science B.V. All rights reserved.
PII: S0531-5131(01)00035-8

This method only works in anatomical regions where the motion is assumed to be negligible between image acquisition time and the operation and is, therefore, limited to regions of the body where the anatomy is relatively stationary.

For operations where the anatomy undergoes motion, surgeons must resort to either open-MR or fluoroscopy for guidance. While open-MR systems provide real-time volumetric imaging during surgery, their cost prohibits widespread adoption. Fluoroscopy is much more common, but provides only 2D projection-mode images via X-ray and exposes the patient and surgeons to ionizing radiation. In contrast, ultrasound imaging is an inexpensive real-time volumetric imaging modality that does not impose any harmful bioeffects on the patient. Therefore, we focus on developing a volumetric ultrasound imaging system for surgical guidance.

cMUT transducers provide large bandwidth, good sensitivity and a potential for electronic integration and are, therefore, an attractive alternative to their piezoelectric counterparts [2]. We have been successful at constructing cMUT arrays with more than 100% fractional bandwidth, twice that of piezoelectric transducers. With this improved bandwidth of cMUT arrays, higher spatial resolution is achieved. The superior sensitivity of cMUT technology makes it an attractive choice for 2D array construction, where the element size is critically limited by the sampling criteria in both dimensions (imaging requires element spacing less than or equal to half a wavelength). For 1D arrays, element sensitivity is not as critical because lengthening each element in the elevational direction can increase its total area. cMUT arrays are fabricated on silicon using standard IC processes, allowing front-end electronics, such as switches, amplifiers and analog-to-digital converters, to be easily integrated with the transducer array.

We have successfully fabricated 1D and 2D rectangular cMUT arrays of various sizes. Testing and characterization of these arrays, such as measurement of bandwidth and sensitivity, have been performed [2]. A general-purpose experimental setup has been established for testing of ultrasound imaging methods employing cMUT arrays. Initial pulse-echo images have also been constructed [3].

2. Materials and methods

2.1. Proposed volumetric system

The proposed volumetric imaging system employs a two-dimensional 16×16-element cMUT array. The real-time image reconstruction is achieved using our novel coherent subarray-processing algorithm. Front-end processing consists of 16 parallel channels to handle 4×4-element subarray data acquisition. The A-scans are collected from all channels by multiplexing the 4×4-subarray across the entire 16×16 cMUT array. The front-end electronics consist of two separate modules, one for the analog front-end (AFE) circuitry and another for the analog-to-digital converter (ADC). The AFE circuitry performs transmit/receive mode switching, preamplification, time-gain compensation and filtering of the received signals. The ADC circuitry has a custom-designed pipeline architecture to digitize the incoming signals from a 16-channel subarray simultaneously. These two modules can be integrated onto a single chip and are to be flip-chip bonded to the cMUT array in order to form the overall front end of the system.

A significant advantage of digitizing the received echo signals within the probe itself is that the signals can be transmitted without loss to the ultrasound base unit. The high-speed digital communication link between the probe and the base can be made with a single shielded cable between the two. This method eliminates the need for a large number of shielded coaxial wires bundled into an excessively large cable.

The system has been designed to be most suitable for surgical applications where the imaged region is relatively small and access to the region is limited. The system is designed to operate at a center frequency of 5 MHz. The Nyquist sampling criteria requires that the square element dimensions are chosen to be less than $\lambda/2$. For a narrowband system operating at a center frequency of 5 MHz, 150 μm/side would be suitable. However, due to the wideband response of the cMUTs, the elements will need to be even smaller, depending on the maximum frequency component of the transmitted pulse. If 150 μm is used, the total array size is 2.4 mm^2. The physical dimensions of the array make it suitable for use within the working channel of an endoscope during minimally invasive surgery. The system will acquire volumetric images at 15 frames/s, where a volumetric image scans a conical volume with a 90° solid angle and 5-cm depth. The array and a portion of the beam space are shown in Fig. 1.

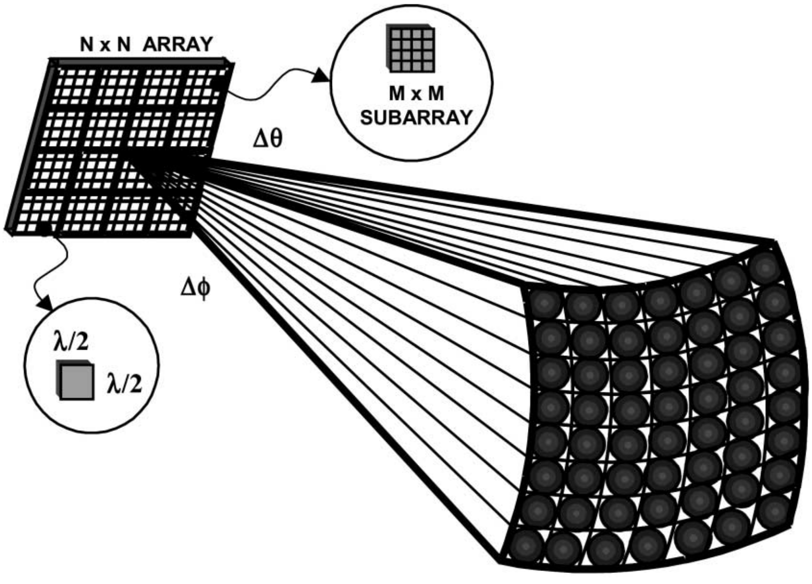

Fig. 1. Beamspace of the 2D cMUT array. The pyramidal volume is swept out by beams steered in θ and ϕ. The 16×16-element array is divided into 16 4×4-element subarrays.

Fig. 2. Setup of experimental system. Left: Photograph of equipment. Right: Block diagram corresponding to key components of the system.

2.2. Experimental system

As a first step towards the development of the described volumetric system, we have designed an experimental setup for testing the imaging capability of the cMUT arrays (Fig. 2). The front-end electronics provide for a single transmit channel and four parallel receive channels, determined by the number of channels available on the data acquisition board. A switching network immediately precedes the transducer array for selecting individual transmit and receive elements. The switches allow the pulse to be transmitted on any single element in the array and the received echo signal to be recorded from four other elements simultaneously. A PC-based digital interface board selects the transmit and receive switches. The received signals are amplified and then digitized with a 20 MHz sampling rate and 12-bit resolution with a PC-based data acquisition board. A complete data set consists of A-scans collected from all combinations of different transmit and receive channels. A LabView user interface provides easy acquisition of all A-scans in a short time. Using the acquired data, any beamforming technique can be emulated in software alone.

Testing of the arrays is done in a water-filled tank measuring roughly 0.5 m^2 by 0.3 m tall. Steel wires spaced 2.8 cm apart cross the tank such that they intersect the imaging plane perpendicularly.

3. Results

3.1. cMUT characteristics

Our group has been successful at fabricating cMUTs of various sizes. Shown in Fig. 3 are 64-and 128-element 1D arrays and a 128×128-element 2D array. The frequency response of these transducers has been measured to be flat up to 10 MHz.

3.2. Point spread function simulations

The point-spread function (PSF) illustrates how the image reconstruction from data collected from a point source in the ultrasound field would appear. Array and beamform-

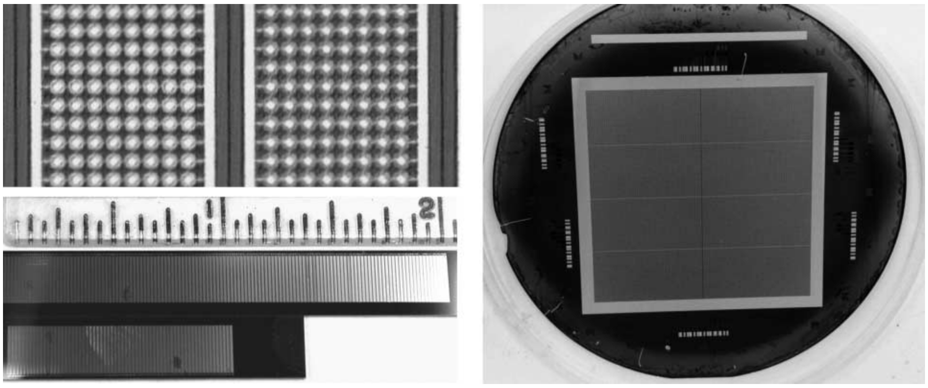

Fig. 3. cMUT arrays. Top-left: Individual cells that form an array element. Bottom-left: 64- and 128-element 1D arrays. Right: 128×128-element 2D array.

ing designs can be evaluated by comparing their PSFs. The width of the PSF mainlobe provides an indication of the resolution that can be achieved. Fig. 4 shows PSF simulations for both 1D and 2D arrays.

3.3. Experimental image results

A 2D image has been reconstructed from raw pulse-echo data taken from a 16-element 1D array (Fig. 5). A-scans from all combinations of different transmit and receive

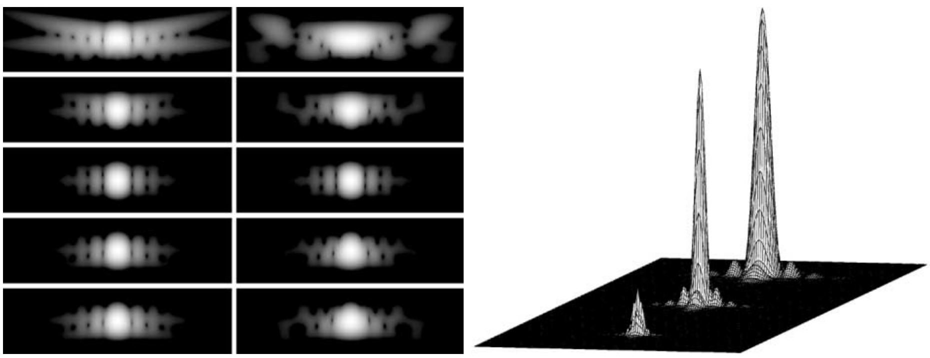

Fig. 4. Numerical simulations of point spread function. Left: 1D array PSFs for 64-element array. The left column shows the PSFs for full array beamforming, and the right shows the results when four subarrays are used. The transmit and receive focal points are at 2, 4, 6, 8 and 10 times the aperture width. PSFs are displayed on a 40 dB compressed logarithmic scale. Right: 2D array PSFs at 2, 6 and 10 times the aperture width away from the array center. Amplitude displayed on a linear scale.

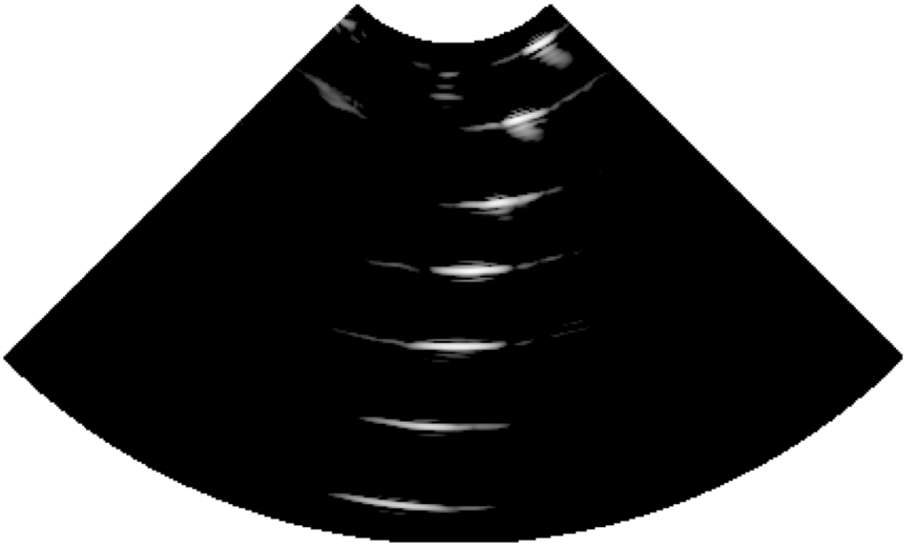

Fig. 5. Reconstructed image. Image of wire phantom reconstructed from pulse-echo data collected using a 16-element cMUT array. The beams scan a 90° sector, the imaging depth is 15 cm, and the image is displayed on a 30 dB log-scale.

elements were collected. The image was constructed using offline dynamic transmit and receive beamforming.

4. Discussion

4.1. Volumetric imaging using cMUTs

The characteristics of cMUT arrays make them viable candidates for 2D ultrasound arrays for real-time volumetric imaging. The significant improvements in bandwidth and sensitivity as compared with piezoelectric transducers provide an opportunity for exploring new beamforming algorithms to achieve enhanced image quality. The use of subarray processing allows real-time imaging and reduces the number of front-end processing channels so that the front-end integrated to the array can be mounted into a miniature probe. The size of the current 16×16-element array is such that it will fit inside of a 5-mm endoscopic channel, providing surgeons with 3D ultrasound during endoscopic and laparoscopic surgery.

4.2. Surgical benefits

The ability to perform real-time intraoperative volumetric scanning should prove to be an extremely valuable tool for surgical navigation. This technique would be applicable not only to traditional open surgery, but also to the rapidly advancing field of minimally invasive intervention. Ultrasound is the ideal imaging method to provide this surgical guidance due to its safety, portability and ease of use. Frameless stereotactic imaging has had a significant impact in neurosurgery. The introduction of real-time 3D ultrasound in the operating room will further the field of image-guided surgery by allowing other applications, such as oncologic surgery of the liver, kidney and pancreas. Current image-guided surgery techniques have already extended the vision of the surgeon to anticipate dissection of surgical planes and avoid injury to critical anatomic structures as well as assuring adequate surgical margins for tumor resection. This vision will be broadened to surgery performed in nonstationary anatomical regions.

References

[1] R. Shahidi, R. Tombropoulos, R. Grzeszczuk, Clinical applications of three-dimensional rendering of medical data-sets, Proc. IEEE 86 (3) (1998).
[2] Ö. Oralkan, X. Jin, F. Degertekin, B. Khuri-Yakub, Simulation and experimental characterization of a 2-D capacitive micromachined ultrasonic transducer array element, IEEE Trans. UFFC 46 (1999) 1337–1340.
[3] Ö. Oralkan, X. Jin, K. Kaviani, A. Ergun, F. Degertekin, M. Karaman, B. Khuri-Yakub, Initial pulse-echo imaging results with one-dimensional capacitive micromachined ultrasonic transducer arrays, IEEE Ultrason. Symp., 2000.