A COMPUTER-CONTROLLED TRANSDUCER FOR REAL-TIME THREE-DIMENSIONAL IMAGING

D.G. Bailey†, J.A. Sun‡, A. Meyyappan, G. Wade
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106, U.S.A.

K.R. Erikson§
InnoVision Medical, Inc.
Irvine, CA 92714, U.S.A.

ABSTRACT

Existing ultrasonic transducers and associated imaging systems are not ideal for high-resolution real-time three-dimensional imaging. Two mechanisms are required in such applications: dynamic focusing, and two-dimensional electronic scanning. These mechanisms are incorporated in a new computer-controlled acoustic transducer. This transducer is divided into a large number of individual acoustic elements, creating a two-dimensional phased array.

Dynamic focusing is accomplished by phasing the separate zones of a circular zone pattern formed on the transducer. Two dimensional scanning may be achieved by controlling the transducer via a two-dimensional shift register.

The advantages of an imaging system using this transducer over existing imagers are that (1) the images are derived from data at sample points in a cube-based matrix as opposed to a stack of sector scans, (2) the resolution is better by an order of magnitude, (3) the transducer patterns are completely programmable enabling the device to be optimized for different depth ranges, and (4) the transducer is fabricated as a single unit as opposed to an array of discrete transducers.

† Current Address: Image Analysis Unit, Massey University, Palmerston North, New Zealand.
‡ Current Address: Department of Radio Engineering, Beijing University of Posts and Telecommunications, Beijing, People's Republic of China.
§ Current Address: Diasonics, Inc., 1565 Barber Lane, Milpitas, CA ~~95305~~. 95035

INTRODUCTION

Acoustic imaging is the technique of using sound waves to obtain an image of the spatial distribution of the acoustic properties of an object. Since acoustic energy yields a view of an object not available with other forms of energy, the exploration of acoustic imaging has attracted many researchers working on a wide variety of applications.

One of the most important applications for an acoustic imaging system is in medical diagnosis. Since biological tissue is semitransparent to sound, it may be imaged with excellent contrast. Cancerous or other diseased tissue can frequently be distinguished from normal tissue in an ultrasonic image[1]. For this reason, there is an increasing enthusiasm among physicians for ultrasonic diagnosis in many fields of medicine involving most parts of the anatomy.

To be practical for medical use, an acoustic imaging system must satisfy a number of requirements. Of particular importance are real-time capability and high sensitivity[2]. In some applications, the ability to obtain three-dimensional images is also important. Real-time capability permits relative motion between the object and the system so that the position of either can be manipulated during imaging to produce the best result. Such capability also allows the study of dynamic biological processes. High sensitivity permits operation at power levels low enough to ensure patient safety.

Existing ultrasonic transducers and associated imaging systems are not well suited for obtaining three-dimensional images in some applications, such as ophthalmic imaging. To obtain three-dimensional images, currently available sensors must be either manually or mechanically scanned[3]. Manual scanning precludes real-time operation, and systems which employ mechanical scanning are too bulky for imaging small objects, such as the eye. Electronic scanning using a phased linear array of transducers is capable of forming good two-dimensional images, but requires mechanical scanning for the third dimension[4]. Such systems also suffer disadvantages stemming from complex system electronics and transducer size. Although transducers which use some form of acoustic lens for focusing are able to achieve high resolution, the depth of focus is usually very poor[5].

THREE-DIMENSIONAL IMAGING

Three-dimensional images may be formed in the following manner. A single pulse of ultrasonic radiation is transmitted and echoes from the various tissue interfaces are received. The position of the reflecting interface in the axial direction may be inferred from the round-trip propagation time of the pulse. This provides one-dimensional depth information. Information about the other two dimensions may be obtained by launching a sequence of pulses in a two-dimensional scanning pattern.

Two mechanisms are required to obtain high resolution three-dimensional images. First, a mechanism for lateral and longitudinal focusing of the pulse is required. Second, a mechanism for scanning the pulse laterally over a two-dimensional pattern is needed.

Dynamic Focusing

To achieve lateral focusing from a planar transducer, an aperture pattern consisting of a set of concentric rings is required. The simplest such arrangement is a Fresnel-zone pattern which has each ring or zone connected to a common signal lead[6] since the

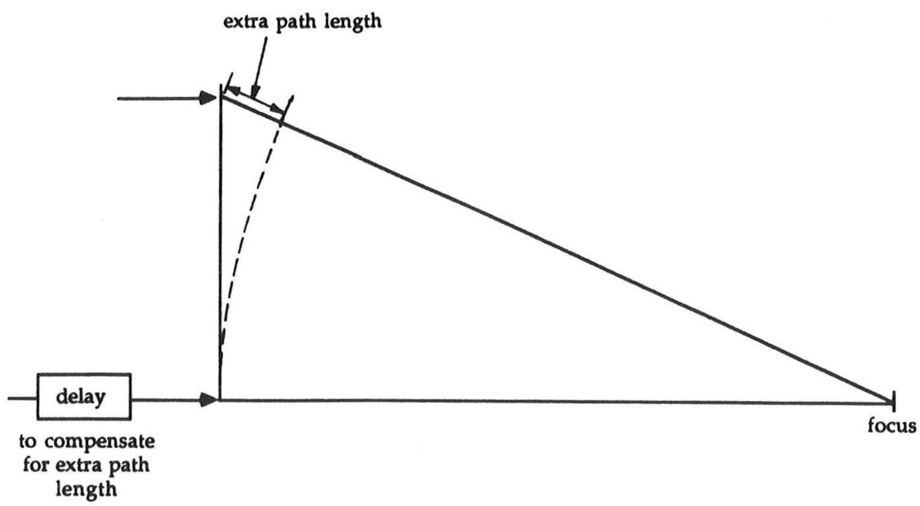

Figure 1. The use of delays to compensate for different path lengths from each ring to the focus.

difference in path lengths between the focus and the rings is an integral number of wavelengths. However the depth of focus of such strongly focused systems is very small.

An alternate arrangement is to use a pattern consisting of a small number of rings to transmit a weakly focused pulse. The aperture must be small and the pulse weakly focused so that it remains in focus over the complete depth range of interest. Focusing action is accomplished by inserting time delays in the signal feeds to each ring in such a manner that the pulses arrive at the focus point simultaneously (figure 1). A similar focusing action is used while receiving the echoes. As with transmission, delays are inserted into the signal leads from each ring to compensate for the different path lengths from the focus to each ring. By dynamically adjusting these delays as the echoes are being received, it is possible to scan the focus in the axial direction. By scanning the focus in such a manner that the transducer is always focused at the point from which echoes are being received, it is possible to achieve very good lateral resolution, as illustrated in figure 2. By expanding the aperture as the focal length is changed, keeping a constant f number, the resolution remains uniform over the complete scan range[7].

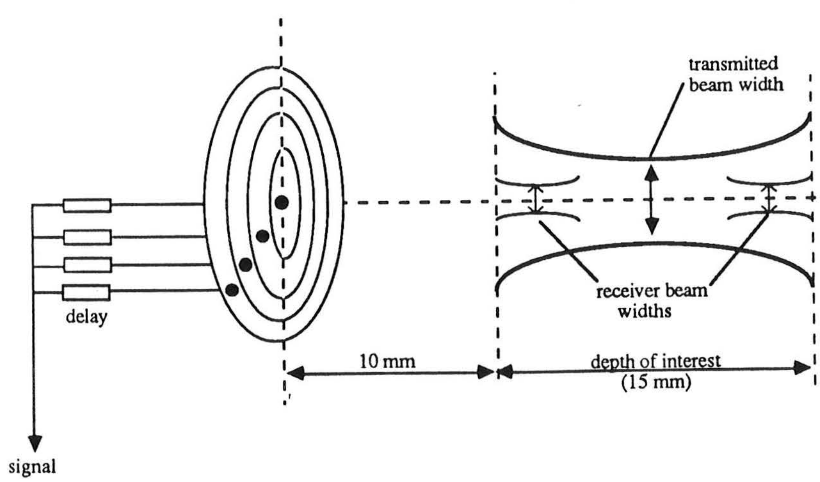

Figure 2. Schematic diagram illustrating the approach for achieving lateral and longitudinal focusing.

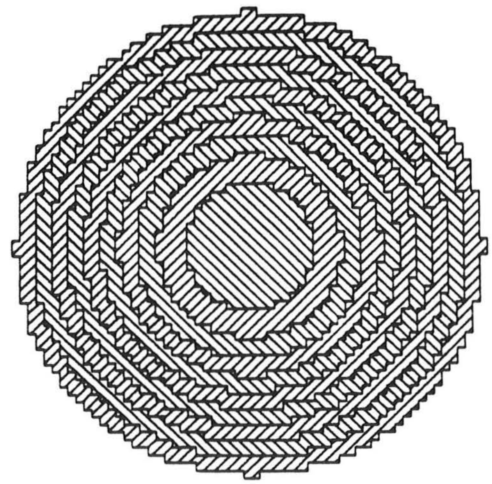

Figure 3. A typical aperture pattern showing 10 zones.

Two-Dimensional Scanning

Scanning the pulse may be accomplished by scanning the circular aperture patterns in two dimensions[6]. One way of doing this is to have the transducer fabricated as a two-dimensional array of small elements. Any desired pattern may be synthesized as a union of individual elements. An example of a typical aperture pattern is shown in figure 3. By shifting the pattern across the array, the position of the focus also shifts.

To illustrate this concept in more detail, consider a pattern consisting of only a single ring. A piezoelectric plate would be used for acoustic wave generation and as a substrate. As shown in figure 4, one side of the plate would be covered with a metal ground electrode and a two-dimensional switch array would be fabricated on the other side. One of the two terminals of each switch is connected to an electrode on the plate, while the other terminal is connected to a common lead or signal line. Each switch is controlled separately by a computer-generated signal via a two dimensional shift register. The transducer aperture is created by turning on the switches in the desired pattern through the loading of this pattern into the two-dimensional shift register. By shifting the data within the shift register, the pattern of switches turned on, and consequently the transducer aperture pattern, are shifted. By scanning the data in two-dimensions in the shift registers, it is possible to obtain image information in the two lateral dimensions.

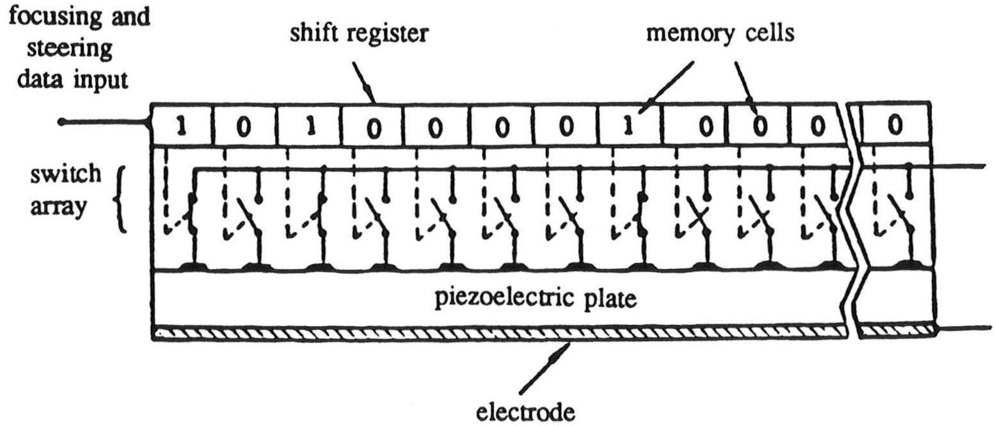

Figure 4. Schematic diagram showing a switching arrangement for the transducer.

CONTROLLING THE TRANSDUCER

The scheme described above would require a separate set of switches, and a separate two dimensional shift register for each ring. A more practical method of providing multiple signal lines and requiring only three sets of shift registers is as shown in figure 5. A separate signal line is fed to each column within the transducer array. One set of switches, and an associated shift register, connects the column signal line to the transducer elements, as in the case described above. Each column signal line services a separate ring in the transducer pattern, although each ring will have several column lines connecting to it. Since adjacent column lines may be allocated to different signal lines, it is necessary to distribute the signal from the signal lines to adjacent elements. This requires two more sets of switches, and associated shift registers, one set for connecting adjacent elements horizontally, and another for connecting elements vertically. By shifting the three patterns contained in the three shift registers synchronously, it is possible to scan the transducer pattern in two dimensions in the same manner as described earlier.

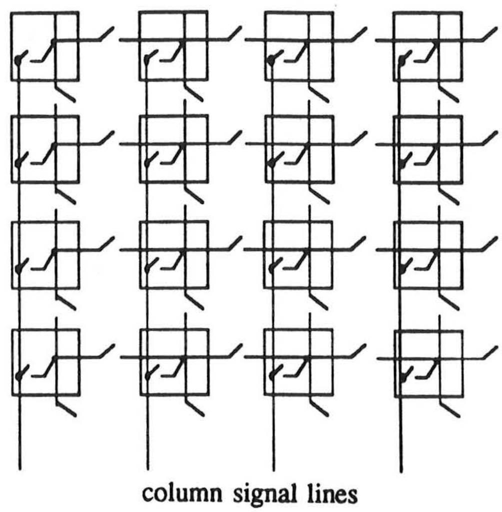

Figure 5. A practical method of providing multiple signal lines.

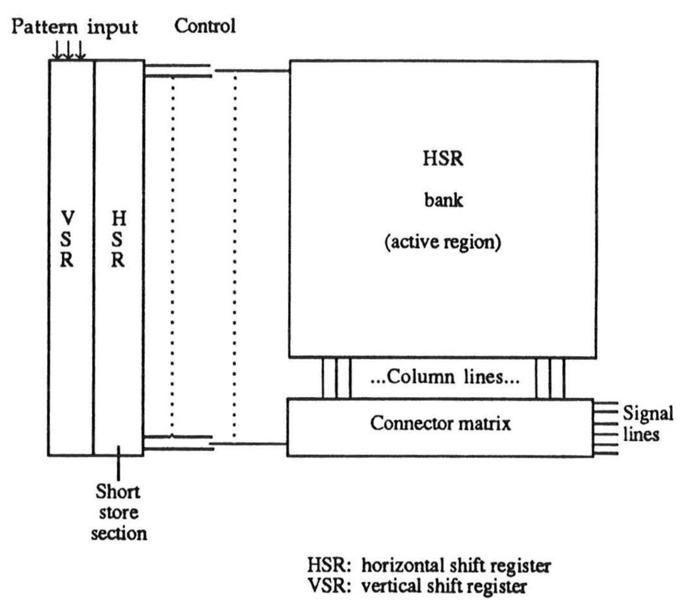

Figure 6. Arrangement of two-dimensional shift registers for loading and scanning the patterns.

The necessary patterns may be loaded and scanned in real time if the two-dimensional shift registers are arranged as shown in figure 6. The two main parts are a bank of horizontal shift registers (HSRs), and a vertical shift register (VSR). The horizontal shift-register bank is used to scan the pattern from left to right in the figure. As the pattern is shifted, a new column of data is loaded in on the left via the vertical shift register. This form of multiplexing simplifies the problem of sending in the large volume of data required to control the patterns. Below the active section is another horizontal shift register bank controlling a crossbar type of connection matrix. The pattern in this bank is used to control switches connecting the column lines to the individual signal lines.

If we assume that the transducer array consists of 100×100 elements, then 299 separate horizontal one-dimensional shift registers are required in the horizontal shift register bank (because there are only 99 rows of switches connecting the elements in the vertical direction). Since each of the three sets of switches for each row of the device are independent, it would be convenient to load the information via three parallel vertical shift registers. The system would work as follows. The first half of the pattern would be loaded into the horizontal shift-register bank which controls the switches permitting a pulse to be launched from the appropriate position and the echoes to be received. The maximum round trip propagation time is about 40 microseconds in ophthalmic inspection applications. During this time the set of vertical shift registers would be used to load two columns of data into the short store section. If there are 15 signal lines, each column of data requires 105 clock cycles (100 cycles for the HSRs and 15/3 for the connector matrix). With a 5 MHz clock, the two columns may be loaded in 42 microseconds. Two columns of data are loaded each time since the lateral resolution is approximately two element widths. The pattern is moved right by two columns, the new data being shifted into the left-hand edge of the horizontal shift-register bank. Then a new pulse is launched. This process is repeated until the pattern center reaches the far side of the array. When the pattern for the next row is shifted into the horizontal shift-register bank, the remaining part of the old pattern is shifted out. The time required to obtain a $50 \times 50 \times 50$ three-dimensional image is 147 ms or a rate of 6.8 images per second. This assumes a 5 MHz clock, 105 cycles to load each column and a pattern radius of 40 elements requiring a total of 140 columns to be loaded.

If a storage section is fabricated on the chip, the 40 columns corresponding to a pattern for a next row may be loaded while the pattern for the current row is being scanned. This reduces the time required to 105 ms or a rate of 9.5 images per second. It is not easy to obtain higher speeds than this, since the round trip propagation time of each pulse is about 40 microseconds.

The operation of the switch registers, and hence the loading and shifting of the patterns on the transducer, and the launching of the acoustic pulses will be controlled by a computer. Thus, a computer-controlled acoustic transducer (ComCAT) will incorporate both the dynamic focusing and the two-dimensional beam scanning described in the previous section. A block diagram of the complete system is shown in figure 7.

SIMULATED RESPONSE

The focusing properties of the transducer were determined by calculating the near-field diffraction patterns of the apertures. In computing the patterns we assume continuous waves rather than pulses. Nevertheless, the calculated patterns provide a reasonably accurate indication of the lateral resolution. Figure 8 shows the amplitude patterns on transmit and receive. Since the effective aperture pattern is the product of the transmit

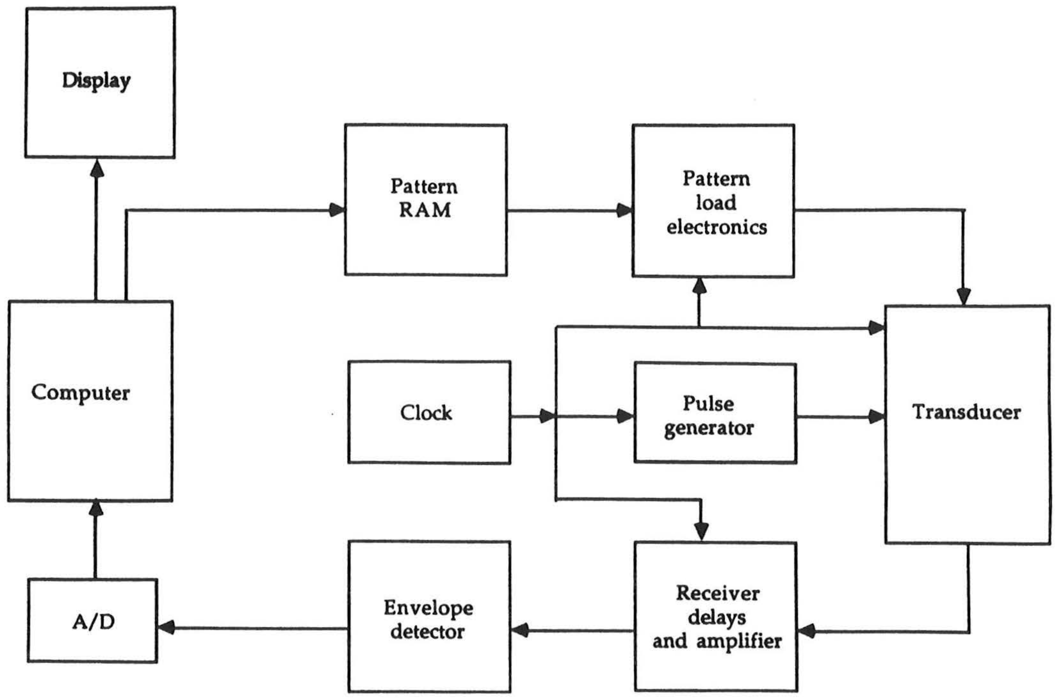

Figure 7. Block diagram of the complete system.

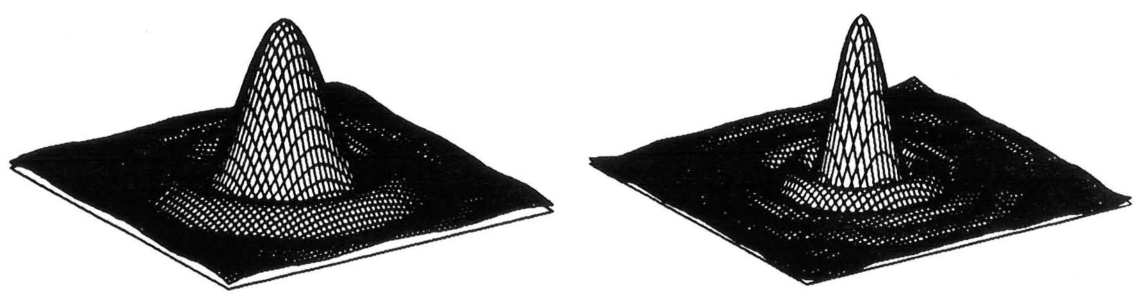

Figure 8. Simulated aperture patterns at 15 mm range. (a) Transmit. (b) Receive.

and receive patterns, the combined intensity patterns are shown in figure 9, using both a linear and a logarithmic scale.

The lateral resolution is usually defined by the point at which the pressure amplitude falls by 3 dB from its peak value. On transmit, the resolution varies from 0.40 mm to 0.93 mm, depending on the range (from 10 mm to 25 mm). On receive, the effective resolution is approximately constant at 0.33 mm. The combined response gives an effective imaging resolution which varies from 0.25 mm (at 10 mm range) to 0.33 mm (at 25 mm range). The first side lobe is down by –20 dB to –30 dB, compared to the main lobe with the best response at the 15 mm range.

As mentioned, these results only give an approximate indication of the true resolution and side lobe levels since continuous waves rather than pulses were assumed. We are currently analyzing the system to determine the expected performance under pulsed operation.

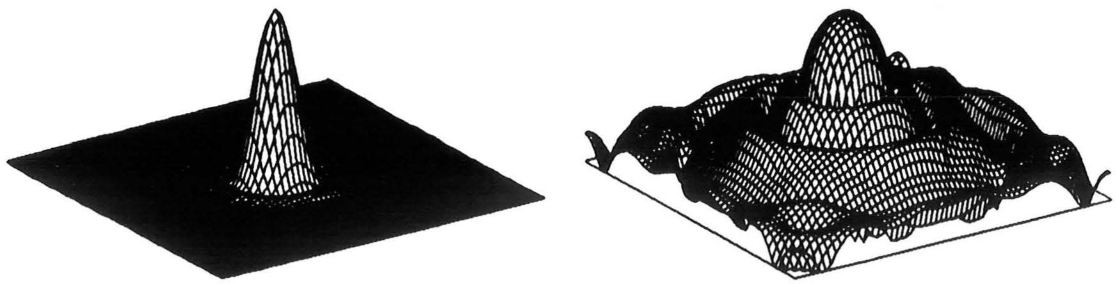

Figure 9. Simulated transducer response. (a) Amplitude using a linear scale. (b) Intensity using a logarithmic scale.

COMPARISON WITH EXISTING SYSTEMS

In recent years, there has been two tendencies in research to enhance the capabilities of B-scan systems. One of these is to improve the imaging quality and reduce the system complexity of the commercially available linear phased array[8,9]. Systems using this technique are capable of providing electrical beam scanning and focusing in one dimension. However, this technique suffers in at least three respects: (1) Image quality is often disappointing due in part to the existence of high side lobes in the beam pattern[10]. (2) The systems are complicated and are therefore expensive[11]. (3) As mentioned above, this technique is only capable of providing electrical beam scanning in one dimension, rather than in two dimensions. In situations where volumetric images are required, the beam scanning in the direction perpendicular to the scanning plane must be performed either manually or mechanically.

Another research tendency has been to explore the capabilities of systems using annular transducer arrays[12]. This includes the use of transducers constructed with a number of concentric circular rings[13] or a single annular ring aperture consisting of a number of separated segments[14]. The annular array technique is capable of performing two-dimensional beam focusing which provides better sensitivity and lateral resolution than those of linear phased arrays[15,16]. Although such systems are relatively simple, it is very difficult to effectively incorporate electrical beam scanning.

An imaging system that uses ComCAT does not have these difficulties. ComCAT, as described above, employs a pattern of concentric circular rings for two-dimensional focusing and a switch-register bank for electronically scanning the beam in the two lateral dimensions. This enables a system with ComCAT to obtain high-resolution volumetric images in real-time. The inherent flexibility of ComCAT also permits the system to operate in more conventional A- and B-scan modes.

CONCLUSIONS

The advantages of an imaging system that uses ComCAT over existing imagers are that the images are derived from data points on a cube-based matrix instead of a stack of sector scans, the resolution is better by an order of magnitude than that obtainable from other three-dimensional systems, the transducer patterns are completely programmable so that the device can be optimized for different depth ranges, and the transducer is fabricated as a single unit as opposed to an array of discrete transducers.

The techniques available with ComCAT provide a number of powerful features which are frequently needed in medical diagnosis. A ComCAT system can have both two-dimensional beam focusing and two-dimensional electrical scanning and still be inherently simple to construct and operate. The system could be built as a small hand-held acoustic probe making it particularly attractive for ophthalmic inspection.

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REFERENCES

1. G. Wade, Ultrasonic Imaging by Reconstructive Tomography, *in* "Acoustical Imaging," 9:379, K. Wang, ed., Plenum, New York (1980).
2. K. R. Erikson, F. J. Fry, and J. P. Jones, Ultrasound in Medicine - A Review, *IEEE Trans. Sonics Ultrason.*, SU-21:144 (1974).
3. J. F. Havlice, and J. C. Taenzer, Ultrasonic Imaging Using Arrays, *Proc. IEEE,* 67:484 (1979).
4. P. N. T. Wells, and M. C. Zilskin, eds., "New Techniques and Instrumentation in Ultrasonography," Churchill Livingston, New York (1980).
5. D. J. Coleman, F. L. Lizzi, and R. L. Jack, "Ultrasonography of the Eye and the Orbit," Lea & Febiger, Philadelphia (1977).
6. J. A. Sun, "Computer Controlled Acoustic Transduction for Real-Time Three-Dimensional Imaging," Ph. D. Dissertation, University of California, Santa Barbara (1989).
7. D. R. Dietz, S. I. Parks, and M. Linzer, Expanding-Aperture Annular Array, *Ultrasonic Imaging,* 1:56 (1979).
8. C. L. Morgon, W. S. Trought, W. M. Clark, O. T. von Ramm, and F. L. Thurstone, Principles and Applications of a Dynamically Focused Phased Array Real Time Ultrasound System, *J. Clinical Ultrasound,* 6:385 (1978).
9. O. T. von Ramm, and S. W. Smith, Beam Scattering with Linear Arrays, *IEEE Trans. Biomed. Engr.*, BME-30:438 (1983).
10. A. Macovski, Ultrasonic Imaging Using Arrays, *Proc. IEEE,* 67:484 (1979).
11. H. E. Karrer, Phased Array Acoustic Imaging Systems, *in* "Physics and Engineering of Medical Imaging," R. Guzzardi, ed., Martinus Nijhoff, Dordrecht (1987).
12. D. Vilkomerson, Acoustic Imaging with Thin Annular Apertures, *in* "Acoustical Holography," 5:283, P. S. Green, ed., Plenum, New York (1974).
13. M. Arditi, W. B. Taylor, F. S. Foster, J. W. Hunt, An Annular Array System for High Resolution Breast Echography, *Ultrasonic Imaging,* 4:1 (1982)
14. C. B. Burckhardt, P. -A. Grandchamp, and H. Hoffmann, Focussing Ultrasound Over a Range Depth with an Annular Transducer - An Alternative Method, *IEEE Trans. Sonics Ultrason.*, SU-22:11 (1975).

15. C. B. Burckhardt, P. -A. Grandchamp, and H. Hoffmann, Methods for increasing the lateral resolution of B-Scan, *in* "Acoustical Holography," 5:391, P. S. Green, ed., Plenum, New York (1974).

16. M. S. Patterson, and F. S. Foster, The Improvement and Qualitative Assesment of B-Mode Images Produced by an Annular Array / Cone Hybrid, *Ultrasonic Imaging,* 5:3 (1983)