Correspondence

Automated Processing of Quad Array Data

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Abstract—A quad array acoustic imaging system used in underwater applications is discussed. In this configuration, a 2*N*-element crossed array results in an effective data aperture equivalent to that of a N^2 filled array. The underwater images of corner reflectors, wooden rods, and a planar letter *E* at an ultrasonic frequency of 152 kHz have shown the feasibility of the system with an electronic scanning capability.

I. INTRODUCTION

Aperture size used in collecting propagating wavefronts limits the resolving capability of imaging systems. The need to reduce the size of the physical collecting aperture and the number of array elements is a problem of fundamental importance in synthetic aperture imaging. The term "synthetic aperture" refers to the simulation of a filled array by the use of some smaller arrays. Examples of these include raster, linear, and cross synthetic aperture arrays to simulate a square filled array [1]. It should be pointed out that the filled array provides much more gain in signal-to-noise ratio.

High resolution scanning of a two-dimensional region which is orthogonal to range clearly requires a transducer array which is itself two dimensional in nature. Considerable reduction in array elements is possible through the use of pattern multiplication techniques in orthogonal linear arrays [2]–[5]. For example, two crossed *N*-element linear arrays can be employed to produce a transmitted fan beam so that the overall system response in terms of composite beam patterns is equivalent to that of a receiving aperture composed of $N \times N$ elements. Such ideas have been further developed to result in the quad array [6] which provides a resolution superior to any other antenna configuration so far designed with the same physical aperture in microwave imaging in terms of number of elements used, cost, and complexity. However, in the microwave application, spatial sampling of each element response was not carried out and imagery was available only be mechanically scanning the complete array system over the target plane.

The purpose of this correspondence is to describe a system with reduced processing time. The feasibility of using the quad array as a spatial sampling device in long wavelength imaging was demonstrated with adequate imaging results [7]. But the time used in the mechanical scanning was prohibitively long; consequently the need for an electronically scanned system became apparent. The quad array with an electronic scanning ability reduced the data acquisition and processing time from three hours to ten minutes.

II. THE QUAD ARRAY

The practical arrangement of a 2*N*-element crossed array to reult in an effective data aperture equivalent to that of a N^2 filled array had been considerably improved without significant increase in complexity. The quad array [7] consists of four linear arrays as shown in Fig. 1. T_1 and T_2, R_1 and R_2 are, respectively, transmit and receive transducers located in the coordinate system (x, y) as indicated. $A(\xi, \eta)$ is a target located in the (ξ, η) plane at a range R and is synthesized from elemental scatterers $d\xi\, d\eta$.

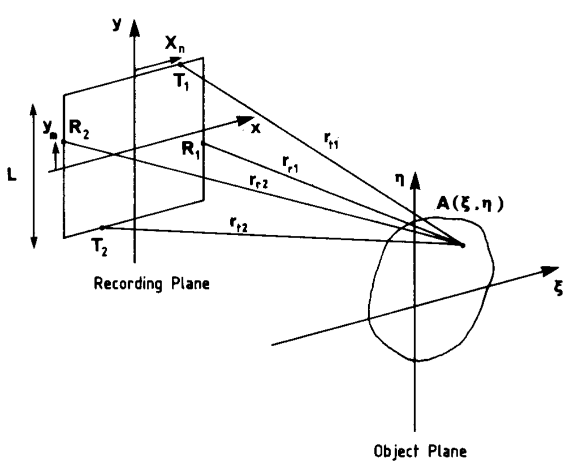

Fig. 1. Quad array configuration.

The path lengths from T_1, T_2, R_1, and R_2 to the general scatterer located at (ξ, η) are given by

$$r_{t1}^2 = (\xi - x_n)^2 + R^2 + (\eta - L/2)^2 \tag{1}$$

$$r_{t2}^2 = (\xi - x_n)^2 + R^2 + (\eta + L/2)^2 \tag{2}$$

$$r_{r1}^2 = (\eta - y_m)^2 + R^2 + (\xi - L/2)^2 \tag{3}$$

$$r_{r2}^2 = (\eta - y_m)^2 + R^2 + (\xi + L/2)^2. \tag{4}$$

Invoking the paraxial approximation and using the scalar diffraction integral [8]

$$\begin{aligned} T(x_n, y_m) &= \iint A(\xi, \eta) \exp jk(r_t + r_r)\, d\xi\, d\eta \\ &= \exp jk \left(2R + \frac{L^2}{4R} + \frac{x_n^2 + y_m^2}{2R}\right) \\ &\quad \cdot \iint A(\xi, \eta) \exp jk \left(\frac{\xi^2 + \eta^2}{R}\right) \\ &\quad \cdot \exp jk \left(\frac{PL\xi + QL\eta}{2R}\right) \\ &\quad \cdot \exp jk \left(\frac{-\xi x_n - \eta y_m}{R}\right) d\xi\, d\eta \end{aligned} \tag{5}$$

where k is the acoustic wavenumber and P and Q are defined as follows:

a) T_1 transmit and R_2 receive; $P = +1, \quad Q = -1$
b) T_1 transmit and R_1 receive; $P = -1, \quad Q = -1$
c) T_2 transmit and R_2 receive; $P = +1, \quad Q = +1$
d) T_2 transmit and R_1 receive; $P = -1, \quad Q = +1.$

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Aside from multiplicative amplitude and phase factors that are independent of (ξ, η), the function $T(x_n, y_m)$ may be found from a Fourier transform of

$$A(\xi, \eta) \exp jk \left(\frac{\xi^2 + \eta^2}{R}\right) \exp jk \left(\frac{PL\xi + QL\eta}{2R}\right).$$

For condition a) the backscattered radiation $T(x_n, y_m)$ from $A(\xi, \eta)$ is translated to center on $x = -x_n, y = -(L/2)$ and the scanning action of T_1 and R_2 results in a recording of the upper left quadrant of backscattered radiation, size $L \times L$. The other combinations of T and R acquire data for the remaining quadrants and the data window obtained is of size $2L \times 2L$. The data collection capabilities of the $L \times L$ are therefore optimized and the resolution obtained is double that for a single T-R pair [4] and superior to that for a single transmit/receive probe which is scanned over the complete aperture of $L \times L$.

III. UNDERWATER EXPERIMENTAL QUAD ARRAY

Fig. 2 shows the operating system of a 32-element underwater experimental quad array. The system is driven by an Apple II computer which is also used as a data acquisition system. The computer controls an A/D-D/A digital interface card, which has 32 digital I/O lines. The timing of the transmitted signal is controlled by the computer's annunciator. The transmit piezoelectric transducers (PC5 lead zirconate) are multiplexed by reed relays, and every relay is enabled or disabled by one of the first 16 digital I/O lines in the digital interface card. An operating frequency of 152 kHz was selected to maximize signal's return. Similarly, the receive transducers are made of the same material and multiplexed by analog switches, using the remaining 16 lines. Any received signal is fed into a quadrature detector for phase information and collected using two of the A/D lines on the interface card. Initial images are produced and displayed using the Apple II computer, which is also connected to a VAX/730 computer through a RS-232 port for data transfer. The software used on the Apple II consists of a BASIC program which calls machine code subroutines for the various switching operations and also calls a machine code fast Fourier transform subroutine to speed up the data acquisition and processing. The same data are also processed on the VAX/730 computer, and the resulting images are displayed using a SIGMA 7000 image display system which has a better resolution display unit.

The experimental underwater quad array is shown in Fig. 3. The array and the multiplexing boards are housed in a high quality sealed diecast aluminum box (260 × 160 × 90 mm, R.S. 507-084). The box lid features an integral synthetic rubber sealing gasket and captive rustless fixing screws. Mounting holes and lid fixing screws are outside the seal making the box hose proof. The quad array arrangement in Fig. 3(a) was produced by cutting small squares with dimensions of 8 × 8 mm and a separation of 3 mm between squares. This was carried out to achieve an angular resolution of 3° and a field of view of + or − 30°. This size square was necessary to accommodate 1 × 1 mm square blocks of transducers shown in Fig. 3(b). The transducers are fixed using a strong adhesive conductive silver paint, and were backed by a square piece of rubber and pressed against the elements in reaction to a square metal plate which was held firmly in place by two screws fixed in two long arms fixed inside the box. Figs. 3(c) and (d) show the receive and the transmit multiplexing board, respectively, and Fig. 3(e) illustrates the mounted array elements. The backing of the transducers was applied to compensate for the large impedance mismatch between the transducer and its air backing. The acoustic impedance of the transducer material is tyically 13 to 23 times that of water, therefore, a quarter-wave impedance matching between the water and transducers was applied in the form of a coat of silver conducting paint and a multiple coating layers of lacquer on the radiating side of the aperture.

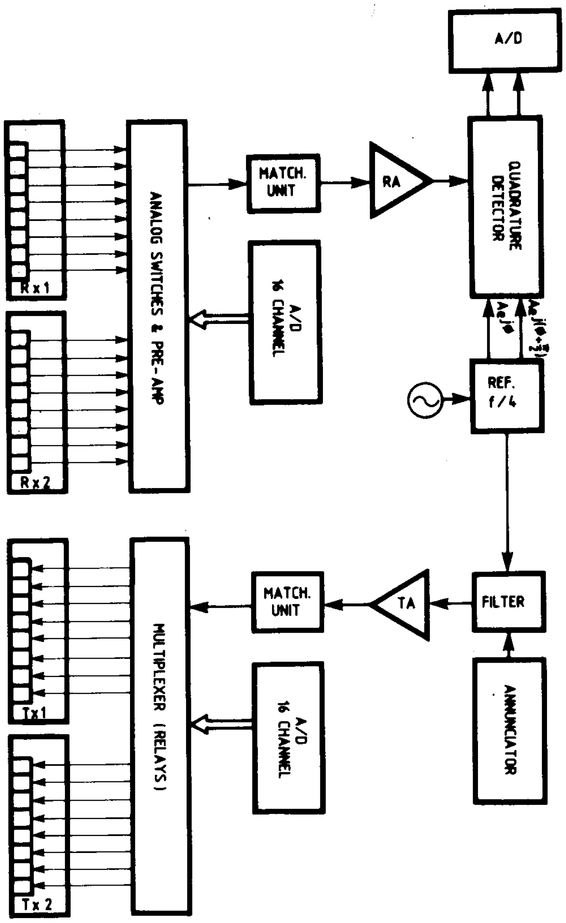
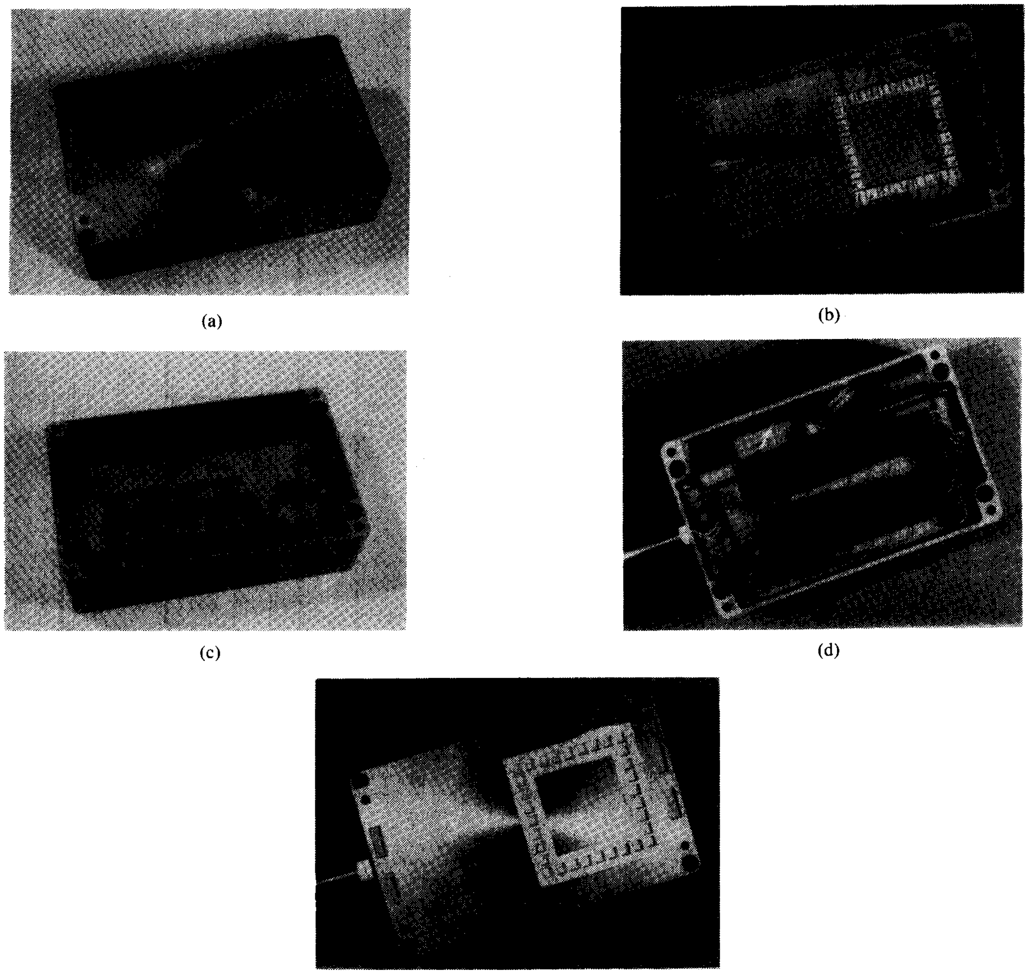


Fig. 2. Quad array experimental setup.

Corner reflectors were selected as initial targets [9], [10] to test the performance and the ability of the ultrasonic quad array as an underwater imaging system. A corner reflector has a scattering cross section which is relatively aspect insensitive, and therefore avoids the need for a precise alignment. Each corner reflector was made of three right angled isosceles triangles with a hypotenuse of 7 cm.

Fig. 4(a) shows the result of imaging a single corner reflector submerged in water at a range of 48 cm and supported by a thin steel rod. It can be seen that the target has been resolved with the precision expected and is clearly presented against a generally low-level background. Fig. 4(b) shows the result of imaging two corner reflectors submerged at a range of 52.5 cm.

Other targets were considered, and Fig. 5(a) shows the image of two wooden rods separated by 10 cm, each rod having a diameter of 2.5 cm and a submerged length of 35 cm at a range of 54 cm. The presence of these two linear features is shown clearly and they exhibit the broken nature so often found in long wavelength images of specular targets. Fig. 5(b) shows the image of a planar letter E of size 25 cm × 15 cm and a horizontal bar width of 5 cm and a vertical bar width of 6 cm. The letter was covered with a plastic material which contained air bubbles inside it. The plastic material



(a) (b)

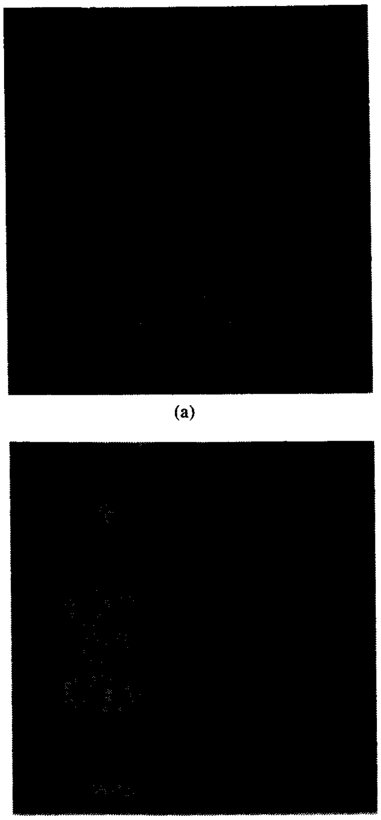
(c) (d)

(e)

Fig. 3. Prototype experimental quad array: (a) quad array arrangement, (b) quad array transducer elements, (c) receive multiplexing board, (d) transmit multiplexing board, (e) array radiating side.

(a) (b)

Fig. 4. Quad array imaging results: (a) one corner reflector, range = 48 cm; (b) two corner reflectors, range = 52.5 cm.



(a)

(b)

Fig. 5. Quad array imaging results: (a) two wooden rods, range = 54 cm; (b) letter E, range = 54 cm.

was selected to reduce the effect of the specular reflection from a planar metallic target. The image shows the bars resolved and the image break-up is again due to specular effect and aliasing from the surface reflection.

IV. CONCLUSION

Direct ultrasonic imaging, with a capability that enables the visualization of images in real time, is an attractive prospect imaging, where a requirement exists for the retrieval of high resolution images at a fast rate. This system provides such a requirement and is also compact in size. A typical application of this system would be on RPV for imaging in a turbid environment, or on small fishing boats for detecting a shoal of fish, or medical imaging applications. Other applications using ultrasound and microwave quad arrays in free space have already been investigated [6], [7].

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Bit Reversal in FFT From Matrix Viewpoint

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***Abstract*—The computation of a minimum and sufficient set of addresses along with corresponding bit reversed addresses, is necessary to do unscrambling in conventional FFT procedures. This correspondence presents a matrix-based interpretation of this problem and typical software and hardware solutions on this basis.**

I. INTRODUCTION

Proper swap is necessary in conventional FFT and similar transforms [1]-[12]. Let one index of each pair of swap indices be called as the primary index and the associated bit reversed index as the secondary index, according to the relative order of computing these two indices. Conventional swap procedures examine all possible indices sequentially from the zeroeth index, for suitability as the primary index, so that every acceptable primary index is less than the corresponding secondary index in positional magnitude. As the basic purpose is to ensure that the final transformed array is correctly unscrambled, the result of any swap procedure should be correct, if the procedure generates a correct set of pairs of primary and secondary indices, irrespective of any sequence of these pairs or whether primary indices are less than corresponding secondary indices in positional magnitude or not. However, a compact coding is hard to conceive, unless the indices are visualized in some order or structure. In-line coding and lookup table coding can generate a correct set of indices in any arbitrary order and can execute quite fast, but require appreciably large memory space. The conven-

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