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MOSAIC: An Integrated Ultrasonic 2D Array System

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Abstract—**An investigation into the development of an ultrasound imaging system capable of customization for multiple applications via the tessellation of in-system programmable scalable modules, or tiles, is presented here. Each tile contains an individual ultrasonic array, operating at +/-3.3V, which can be assembled into a larger 'mosaic' of multiple tiles to create arrays of any size or shape. The ability to form an imaging system from generic building blocks which are physically identical for manufacturing purposes yet functionally unique via programming to suit the application has many potential benefits in the field of ultrasonics. The system is primarily targeted at underwater sonar and non-destructive testing, as defined by the current excitation frequency, but the concept is equally applicable to applications in biomedical ultrasound.**

Keywords-component; 2D array; microelectronics; system integration; miniaturization

I. INTRODUCTION

The motivation for the work reported here stems from the desire to construct 2D arrays of any size and shape capable of 3D beam steering from generic building blocks. Such a system would represent a departure from almost all previous work in ultrasound which has traditionally been highly application specific. In order to construct large arrays from multiple building blocks, it is necessary to encapsulate the ultrasonic array and all the electronics to operate it within the same footprint to enable multiple tiles to sit contiguously to one another. This is markedly different to conventional ultrasound systems, where, aside from overall size, such spatial constraints do not usually exist.

Additionally, such a system requires a totally autonomous module, capable of operating individually or collectively, and as such requires an enhanced level of system integration. All electronics, whether analogue front end, digital signal, communications or control, must be housed within each tile to permit unique operation. This contrasts with most previous research on system integration which has focused largely on integrating the transducer and front end electronics [1]. Our previous research in this area resulted in prototypes of increasing levels of system integration [2] and laid the foundations for the present paper, documenting the next level of system miniaturization, whilst increasing massively the level of functionality.

In our work, we have produced a 4 x 4 element 2D piezoelectric array with a 16 mm x 16 mm aperture, with the entire transmission and reception electronics packaged within the same footprint. This allows multiple tiles to be tessellated to achieve larger arrays, as shown in Fig. 1. In addition, the proximity of the transducer and electronics removes the need for lengthy cabling and hence avoids signal degradation due to cross talk and interference and also leads to improved signal quality due to fewer variations in impedance mismatches over time between the transducer and electronics.

The approach outlined here is based on addressing systems issues and packaging the system in a way that helps meet the requirements of the ultrasound community, including low power consumption and portability. Additionally the electronics require packaging in such a way as to permit the element-to-element spacing to be constant throughout the system irrespective of whether or not the elements are on the same tile. This allows tiles to be positioned contiguously without the element-to-element spacing being adversely affected.

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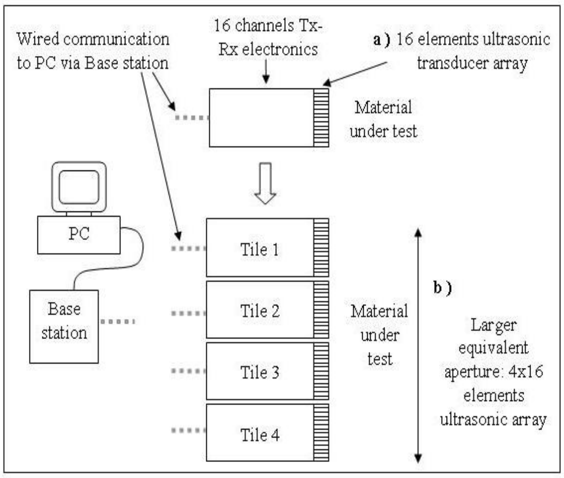

Fig. 1. MOSAIC concept showing (a) a single tile and (b) 4 tiles positioned to give a larger equivalent array in 1 dimension.

II. SYSTEM DESIGN

In order to incorporate the functionality of 3D beam forming, the 16 transmission and reception channels on each tile must be capable of excitation and reception at all times. Coded transmission signals are generated with a field programmable gate array (FPGA). This affords each tile in-system programmability and allows tiles to be physically identical, yet functionally unique in operation. Each channel has individual MOSFET drivers and MOSFETs to generate bipolar signals to excite the transducer. This involves many additional electronics components compared with simpler approaches and thus a resulting increase in space, but is essential for the focusing and steering of beams. The transducer elements can be excited using any coded sequence of any practical length, with timing resolution controllable down to 10 ns due to the FPGA's ability to generate unique, user-defined coded excitation waveforms, maximizing flexibility for use in any application.

All 16 reception channels have individual, adjustable preamplifiers. Digitizing 16 channels requires a compromise between multiple analogue-to-digital converters (ADCs) and multiplexing several channels into fewer ADCs with a resulting loss in sampling resolution. The former solution leads to large increases in power consumption (with ADCs being amongst the highest current consuming devices in a tile). The latter solution requires the multiplexing of the analogue signals at a rate fast enough to avoid undersampling. That this is possible is due to the relatively low ultrasound frequency of 1.2 MHz used in the present system, although it is possible with the present arrangement to increase this up to 2 MHz. In order to maintain oversampling, it was decided to multiplex 16 channels in 2 sets of 8-to-1 multiplexers, feeding a dual 12-bit ADC for maximum efficiency and flexibility in terms of altering the excitation frequency, and, hence the receiver sampling frequency. Most contemporary research on system integration has concentrated on single element systems where such issues are not a concern [3]. However this was found to be one of the most challenging parts of the system due to the limited range of analogue multiplexers available with sufficiently high switching speeds.

Digitized samples are handled in the FPGA and stored in memory on each tile before being transferred to a host PC for processing. By decentralizing a multi-tile system to this extent, it is possible to construct a 2D ultrasonic array network comprising an unlimited number of tiles in any configuration.

III. SYSTEM IMPLEMENTATION

Despite the tight constraints and limited space available, several factors made it necessary to implement the system using off-the-shelf integrated circuit level electronic components. These are mounted on and interconnected by a PCB, their selection taking into account physical dimensions in addition to electrical properties. Fig. 2 shows one side of the electronic circuit used in a tile, implemented using hybrid flexi-rigid circuit boards [4] which fold to allow the entire circuit to fit within the 16 mm x 16 mm array footprint. For this to be possible, the length of the tile would have to be relatively long due to the number of components required in the system. This problem has been reduced and the PCB layout eased in certain respects by dividing the circuits into three rigid strips, with one of the internal layers being flexible to allow the circuits to fold over on each other with the flexible layer carrying interconnecting signals between the rigid PCBs. Ground shields, shown as hatched strips running along the top and bottom of Fig. 2 lie between the rigid boards when the tile is folded, providing additional signal isolation between the rigid circuit boards.

Fig. 3 shows the three rigid PCB strips folded over each other and attached to the transducer via an interface PCB to attach the tiles flexible 'tails' and connectors to the transducer.

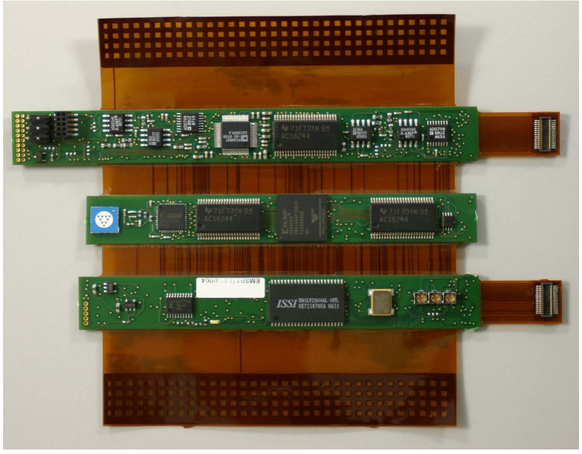

Fig. 2. MOSAIC tile with electronics implemented on a flexi-rigid PCB to enable the electronics to fit within the 16mm x 16mm footprint.

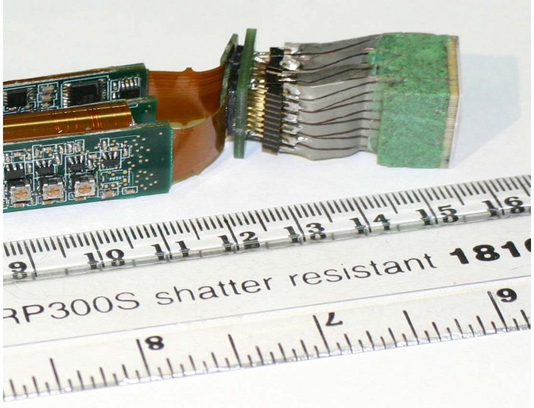

Fig. 3. MOSAIC tile with transducer attached via interface PCB.

Due to dimensional constraints, it is increasingly common for portable handheld array-based systems to have their electronics close to the array. Impedance matching between array elements and electronics can be hard to achieve and maintain in a practical system. Cumulative impedance mismatches over time between the electronics and the individual transducers can greatly impair the signal to noise ratio. One possible solution lies with the avoidance of cables. Previous solutions aimed at direct attachment of the transducer to the electronics have been implemented on the same silicon substrate, as with CMUTs [5], or in the case of piezoelectric transducers, via direct pin attachments from the transducer to the PCB. Both these cases see the transducer mounted physically parallel to the electronics, rather than perpendicular as in the case of the tiles. Perpendicular attachment, whether of a flip-chip bonded transducer [6] or of pins from the transducer direct to the PCB would not give a robust connection so an alternative solution was developed that permits attachment of different transducers, tailoring the system to suit the application. Fig. 4 shows a cross section of the arrangement.

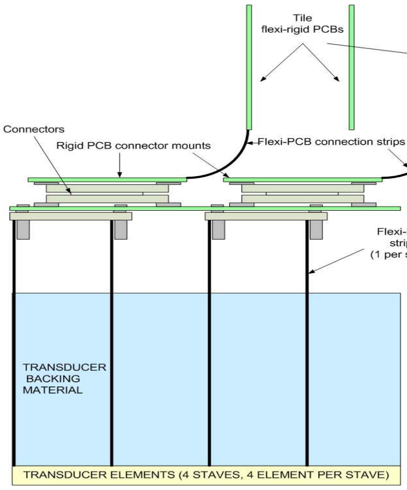

Fig. 4. Cross sectional view of transducer array connections.

IV. RESULTS

Fig. 5. shows the normalized, post-processed, correlated receiver responses for 16 channels in response to the stimulus of a 1.21 MHz 13-bit Barker code at +/-3.3V applied to each element in turn, with the array coupled to a circular aluminum drum of approximately 195mm thickness and 200mm diameter.

After digitization, the received signal is correlated with a copy of the transmitted code using coded excitation with spectral inversion methods [7] and subsequently subjected to a band-pass filter in order to remove the high frequency switching noise present due to the digital switching signals used by the ADC and analogue multiplexers. The effects of the excitation signals can be seen in the region 0 – 10µs with the first back wall echo showing a correlation around 60 - 70µs with a subsequent back wall echo at approximately 126µs.

All array elements were verified as working via several methods including impedance measurement, underwater characterization and crosstalk measurement. Although it can be seen from Fig. 5 that some elements, notably 2, 6 and 10 exhibit weaker echo responses than average, all exhibit similar amplitude levels, to within 6 dB, throughout the plots. There are several possible explanations for this including variations between the elements due to manufacturing processes giving rise to variability in the received signals between channels. This has been noted and documented before [8] in the development of these transducers. In addition, further inconsistencies may be attributed to different gains in the adjustable preamplifiers.

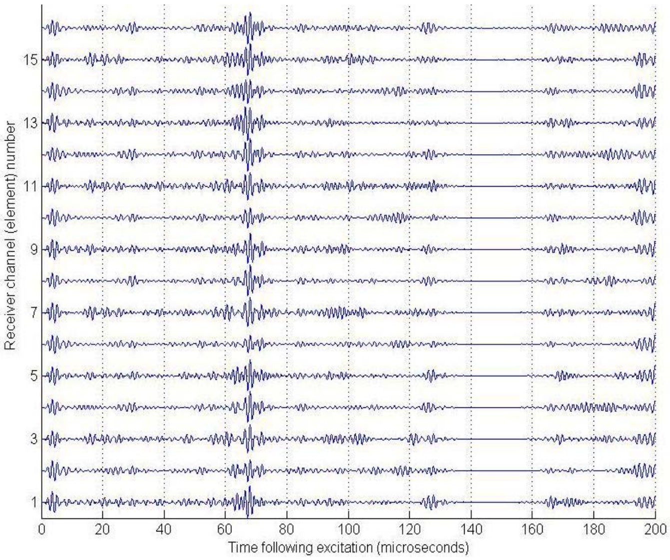

Fig. 5. Post-processed waterfall plot showing all 16 channels in a pulse echo test using a 13-bit Barker code at +/-3.3V. The test block was approximately 200 mm thick aluminum.

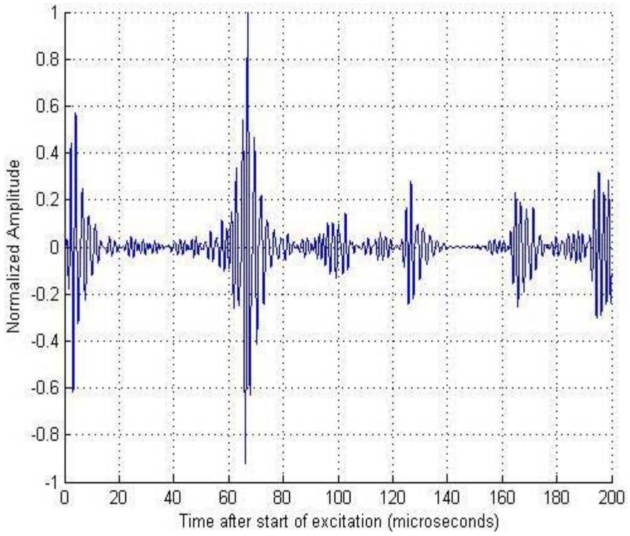

Fig. 6. Receiver response showing the average of all 16 channel responses from the waterfall plot in Fig. 5.

Fig. 6 shows the result of averaging the receiver responses from Fig. 5. The much larger indication of the back wall of the test block relative to other signals indicates that these other signals are relatively uncorrelated and may be attributed to noise in the system.

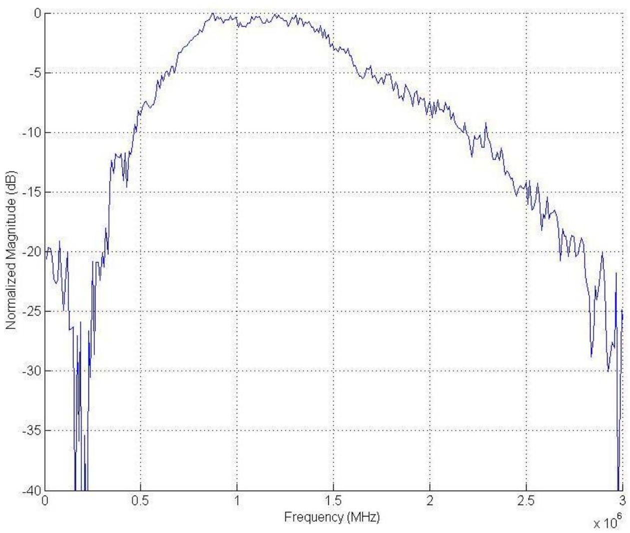

Fig. 7. Frequency response of average of signals from all 16 elements in the array.

Fig. 7. shows an average of the frequency response for all 16 channels in the transducer, obtained by taking the Fourier transform of the echo signal observed around 62 μs in Fig. 5. It indicates that the centre frequency of the array elements is approximately 1.2 MHz and a dynamic range of 40 dB can be seen. An average relative bandwidth of approximately 90% is evident, calculated using the average bandwidth at -6 dB and the average centre frequency of the transducer.

V. CONCLUSIONS

In this paper, the concept of the MOSAIC system has been introduced in the form of an autonomous modular tile designed to provide the necessary flexibility to operate in a wide range of ultrasound imaging applications without incurring substantial redesign costs in moving between applications. The paper documents some of the crucial factors in realizing such a concept from a system design perspective and how such problems were overcome. The system is flexible in many ways, some due to the physical implementation, such as array configuration, number of elements in the array, and choice of aperture. Programmable electronics also contribute to the flexibility in terms of factors such as frequency of operation, length and type of excitation sequence used, and implementation of real time hardware signal processing functionality.

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