MOSAIC: A SCALABLE, MODULAR SYSTEM FOR UNDERWATER ULTRASONIC IMAGING

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1 INTRODUCTION

It is increasingly common for high performance array-based SONAR systems for applications such as target classification to have electronics in close proximity to the transducer array. The avoidance of cables between the electronics and the individual transducers greatly helps to increase the signal to noise ratio. However, the close coupling between the design of the electronics and the transducer array may limit flexibility if the array configuration is to be modified.

This paper presents, as an alternative, the concept of a modular ultrasonic imaging system capable of scalability and modification without redesign. This system can be seen as a mosaic consisting of multiple tiles, each of these tiles in the present case integrating a high-frequency 16-element piezocomposite transducer array together with the electronics necessary for full transmit-receive capability on all 16 channels. The beam forming capability of this mosaic, for example for high resolution target classification, can then be varied according to the number of tiles directly juxtaposed next to one another laterally and the software used to define the system's operation.

The physical footprint of the electronics in this application is obviously a constraint, as this must match the aperture of the transducer array, leading to major challenges in miniaturisation. For example, even connectors and cables are relatively profligate in terms of consumption of space. In the work reported here, it has therefore been chosen to integrate wireless communication for key data transfers and avoidance of connectors through electronic system integration has been utilised.

These and other aspects of the system are discussed in this paper, and the potential for high performance SONAR is considered. The remainder of the paper is divided in three parts. Section 2 provides more information on the basic concept and its potential applications. This is followed by more detailed technical information in Sections 3, 4 and 5, describing the work that has been done so far on the development of the systems electronics and the optimised transducers. In the final part, results of early tests are presented.

2 CONCEPT AND APPLICATIONS

Electronic array SONAR systems and most ultrasonic imaging systems in general are designed for one particular application. This application is typically defined in terms of parameters such as spatial resolution and range which are functions of the operating frequency, number of elements and aperture of the array. It is common practice to design the transducer array that suits the application and separately the electronics, then to combine them. However, it can be argued that the quality of a system could be increased by having the electronics integrated with the transducer.

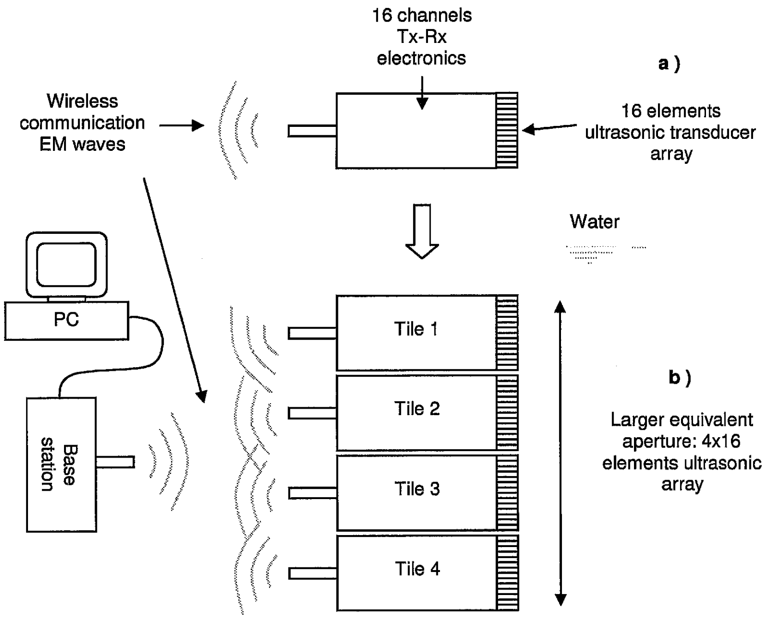

Figure 1: MOSAIC concept
a) A tile comprising a 16-element ultrasonic transducer array and integrated electronics for 16 Tx-Rx channels, also capable of wireless communication,
b) A 64-element equivalent array aperture achieved by positioning four tiles side by side, and communicating data to a base station wirelessly for processing.

If solutions based on integrated electronics are developed on a case by case basis, they are likely to be very costly. For example, a different aperture is required according to the required range, beam widths and resolution of the system and, generally, a transducer array with a different aperture means a new design.

As an alternative, one can imagine making a scalable array by placing a set of sub-arrays side by side. This would allow control of the total aperture of the array and achieve performance optimised for the application under consideration. If subsequently a different aperture is required, one can simply add tiles to or remove them from this MOSAIC transducer array. This is the principal foundation of the MOSAIC concept presented in this paper, as shown in Figure 1: such a system is intended to provide the user with more flexibility in the range of applications without system redesign.

This system would not be optimum and its flexibility would be limited if it were to be driven by standard electronics. Hence, the control electronics should also be scalable so that they comprise the same number of transmit (tx) and receive (rx) channels as the total number of elements in the whole MOSAIC array. Alternatively, of course, the concept can be applied to a receive system only, with separate, simpler transmit hardware, for example to insonify a complete underwater volume.

This concept can be realised by integrating the electronics block with the sub-arrays, bringing many potential advantages.

- From a practical point of view, the size of the system is reduced, as the whole system can be encapsulated within the tiles themselves.
- From an electrical point of view, the avoidance of cables between the transducer and the electronics facilitates noise reduction and electrical matching.
- Having electronics matched to the transducer also allows the possibility to work with smaller voltages, if this is compatible with the application range. This brings the possibility to have low power operation and cabling can be completely eradicated by including wireless communication between tiles.
- To considerably ease the data transfer, wireless communication also permits the elimination of connectors, with implications for reduced space, increased reliability, and increased ease of underwater system design.

The tile operation with electronics integrated behind the transducer array is illustrated in Figure 1. Figure1(a) shows a tile with an array on the right hand side, the electronics block in the middle and an antenna on the left handside representing the wireless communication capability. Figure 1(b) shows four of the tiles juxtaposed next to one another, producing an array with an equivalent aperture four times that of a single tile.

Working with low voltage excitation inherently implies low signal to noise ratio (SNR). An attractive way to increase SNR with modern electronics is to use coded excitation waveforms[1]. The transmit electronics in this technology does not simply excite the transducer with a function that can be approximated to a Dirac impulse or to a gated sinusoid, but with a sequence of "zeroes" and "ones" for the case of codes such as Barker codes and Golay codes, or by varying the frequency of excitation with time in the case of frequency modulation, commonly described as chirping.

The decoding of the received waveform can then be performed using a correlation process. To implement such signal processing techniques, the system has to be highly flexible in terms of the waveforms it generates to excite the transducers. Such a level of flexibility is also required to apply suitable time delays to the excitation of phased array elements in order to achieve the beam forming necessary for electronic beam steering, and indeed the focusing that might be desirable for short-range target classification.

Such flexibility also implies that the electronics should be compatible with transducers working over a wide range of frequencies, the only constraint being the footprint of the electronics that should be smaller than the dimension of the sub-array defined by the spatial sampling used to achieve the desired beam profile. In an extreme case, one can imagine that a user possesses a set of electronics blocks and different sets of ultrasonic arrays for different frequencies which can be interchanged rapidly by simply plugging / unplugging, assuming that a suitable waterproofing solution is found.

Finally, it must be realised that this modular approach of electronics blocks and standardised sub-arrays has significant potential for mass production and simplification of the fabrication processes, potentially simultaneously driving down cost while allowing end users to access optimum performance for their applications.

3 SYSTEM DESIGN

The MOSAIC concept lends itself to scalable solutions as a tile can be used individually or, more usually, as part of a larger system. This requires the individual tile to be as flexible as possible to allow it to be configured to suit the intended application. It must also be capable of performing effectively individually and collectively.

The tiles developed in the work outlined here are fully flexible and capable of transmitting and receiving on any or all transducer elements using excitation sequences of any type of code or length, subject to the limitation of uniform amplitude excitation. Such flexibility is achieved by incorporating the digital electronics within the tile in a field programmable gate array (FPGA). The supplier or end user can then program the tile as desired and two physically identical tiles can have very different functions.

In the present system, the FPGA takes the digitised output from the transducer array and formats it for transmission to a host PC. The presence of an FPGA in each tile decentralises a multi-tile system which is important in order to make the system scalable. The FPGA gives control over the excitation waveforms, allowing any element to be excited with an arbitrary digital code of effectively any length down to 10 ns timing resolution. Suppliers or users can implement their own front end digital post-processing functions on the FPGA. This suits functions like filtering and averaging as these can be pipelined effectively and suit the data flow architecture, making best use of available resources without producing a data bottleneck.

In the present system, the FPGA outputs the excitation waveforms to MOSFET drive circuits to generate bipolar signals for exciting the transducer. The transmission and reception electronics meet at the transducer with the lack of cables between them permitting excitation voltages as low as +/-3.3V to be used to obtain adequate short-range reception signals. These reception signals are still very small with respect to the transmission voltages so careful circuit layout is required to minimise noise from the transmitter circuits affecting detection of signals. Each element has its own adjustable gain preamplifier after which the signals are multiplexed and time gain control is applied. A differential preamplifier prepares the signals for digitisation using a 12 bit ADC.

In the present work, the realisation of the MOSAIC concept was divided into three stages so that the amount of development required between each stage was manageable in terms of increasing system complexity.

- The first stage was designed to demonstrate that the analogue front-end electronics could couple directly to a one-dimensional (1D) transducer array capable of two-dimensional (2D) beam forming and produce adequate reception signals at excitation voltages of +/-20V. This stage also served to demonstrate the electronics required to transmit and receive on all elements in an array and FPGA control of transducer excitation waveforms in terms of timing resolution and ability to alter excitation sequences.

- The second stage, and the one documented in detail in this paper, had multiple objectives. These included implementation of the digital sampling and multiplexing of multiple analogue channels and integration of the transmit and receive electronics with sufficient noise immunity between them to preserve receive performance when used with a 2D array capable of three-dimensional (3D) beam forming. This stage also saw the integration of electronics into an area limited by the size of the array and proved the scalability of all electronics on the transducer array side of the FPGA.

- The final stage will see the integration of the entire system in a multi-tile network and the use of wireless communications between tiles and host and also inter-tile wireless communications to prove that once programmed, the user has created a network of remotely operated autonomous entities. The issue of the tile-to-tile synchronisation is an important one which will be dealt with in this final stage to ensure synchrony appropriate to the application requirements.

As each tile in the MOSAIC system requires the same electronics, whether the system comprises a single tile or multiple tiles, the solution can be said to be truly scalable. This is due to the decentralised nature of the electronics. This potentially improves upon current ultrasonic systems as it permits a generic tile to be used in a large multiplicity of applications, with reprogramming of the FPGA being the only adjustment required. Hence, it demonstrates that a cost effective, generic solution is possible in an area traditionally dominated by application specific solutions.

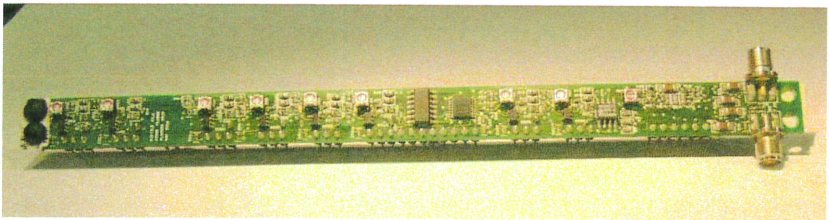

Figure 2: Photograph of the mid-tile electronics block (board 12mm wide)

4 ULTRASONIC TRANSDUCERS

Several array configurations can be envisaged for a tile due to the fact that, as highlighted in Section 3, the system can operate with transducers working over a wide range of frequencies and can operate equally well with 1D or 2D arrays. These arrays must meet only two main conditions.

- The number of elements in the array: the transducer array must be made with 16 elements (or, unusually, less) as the electronics presently has 16 channels;

- The aperture of the array must be the same size as the electronics footprint. In the present case, the electronics has been designed to fit a 16 x 16 mm^2 footprint. A larger array would also be possible but immediate juxtaposition of a smaller array would not be possible because of the dimensions of the electronis.

In the case of a 1D array configuration, the tile dimensional constraint means that the inter-element pitch has to be 1 mm. This also means that any transducer array operating below 750 kHz can be used as a fully-sampled phased array as this is the frequency at which the $\lambda/2$ (half-wavelength) pitch condition necessary for perfect phasing[2] is met. Any higher operating frequencies would lead to spatial undersampling and the potential for grating lobes.

In the case of a 2D array, a 4 x 4 matrix of elements can be fitted within the electronics footprint, giving 4 mm square elements. In this case, the $\lambda/2$ pitch condition necessary for full spatial sampling is respected for operating frequencies below 185 kHz. Any higher operating frequencies would again lead to the possibility of grating lobes.

Although the present publication relates to detection and, most particularly, characterisation of underwater targets, many other potential applications can be envisaged due to the flexibility of the system in accepting alternative transducer configurations. These include other underwater SONAR applications as well as non-destructive testing and biomedical diagnosis. To illustrate the flexibility of the system, in the present work it is planned to investigate several different configurations.

- Fully sampled 2D arrays operating at 1 MHz for NDT. (The wavelength is longer in this case.)
- Fully sampled 1D arrays operating at 750 kHz for underwater imaging
- Fully sampled 2D arrays operating at 200 kHz for underwater imaging.

As for the design of the electronics, a strategy of design through several stages was adopted for the transducer arrays. The first stage, presented here, was aimed at validating fabrication processes and highlighting unexpected technical difficulties. The later stages are designed to focus on fabricating reliably the transducer arrays outlined above, as well as identifying backing materials with the unusually high attenuation coefficients needed to limit the depth of the transducers and integrate them with the electronics in as compact a solution as possible.

The particular transducer array reported in this paper is a 2D array operating at 800 kHz, with a 50% -6 dB relative bandwidth in transmit-receive mode. The manufacture of this array was done using conventional manufacturing techniques[3]. This was made using 1-3 piezocomposite technology[4], which is known for performing better than bulk piezoelectric ceramic technology. This is principally attributed to a greater electromechanical coupling coefficient, an acoustic impedance closer to that of water, and considerably reduced lateral modes, enhancing both the individual array element performance and the performance of the array as a whole.

The present piezocomposite material was made from high-performance, piezoelectrically soft ceramic and a hard-setting epoxy filler. The ceramic volume fraction was 40% and the fabrication process was based on the dice-and-fill method[5]. As a guide to performance, the effective thickness mode electromechanical coupling coefficient of the piezocomposite was measured to be 0.59.

The overall transducer array comprised a matching layer to improving the energy transfer to the front medium (sea water) and a backing layer for damping the resonance of the piezocomposite layer[6]. The matching layer was made of epoxy and the backing material was a mixture of silicone rubber and tungsten particles. Electrical connection was achieved using flexible PCBs and a thin stainless steel casing encapsulated all the layers to provide electrical shielding. A photograph of the completed prototype device is shown in Figure 3.

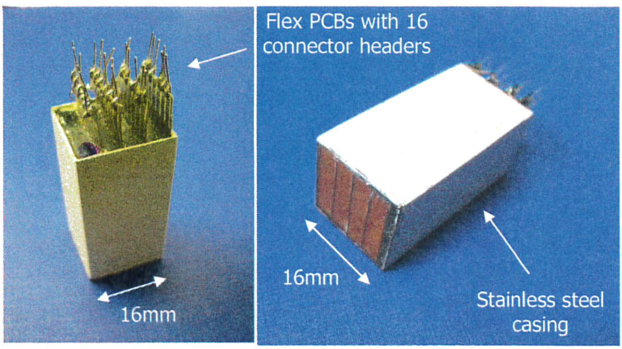

Figure 3: 4x4 element 2D array transducer

5 RESULTS

To obtain preliminary results, the transducer array shown in Figure 3 was connected with the prototype electronics in Figure 2 to perform an underwater pulse-echo test, comprising excitation of the transducer with an electrical pulse to produce ultrasound which propagates through water and reflects off a glass target. The echo is then sensed by the same transducer in receive mode.

To illustrate the capability of the electronics to generate an arbitrary electrical pulse excitation scheme, the transducer was excited with a train of pulses mimicking a code. For the results presented here, the sequence of binary pulses was 1111010100010101, in which each '1' is a bipolar square pulse of total length 1.25μs, corresponding to a single cycle at 800kHz, and amplitude ±10 V. This sequence was chosen arbitrarily and is not intended to optimise SNR after decoding. The recorded waveform recorded is shown in Figure 4(a).

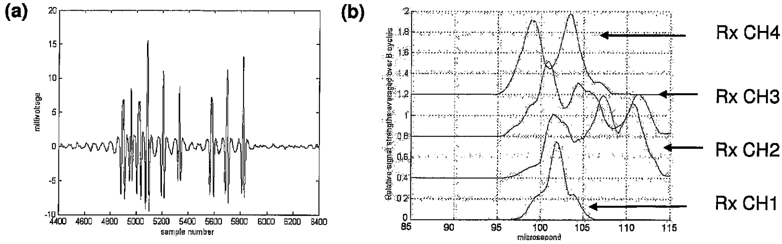

Figure 4: Experimental data from short range underwater pulse-echo testing. (a) Sequence of pulses with excitation 1111010100010101 and (b) excitation on one channel and reception on four different channels, with decoding

The peak-to-peak voltage of the tx-rx pulse is V_{pp} = 25 mV, or -58 dB compared to the excitation signal. Clearly, in this very simple test, the received signal is well above the noise floor, although further work in this area is obviously required. Early tests have also been performed with the system using coding and decoding, with results such as that shown in Figure 4(b). As an indication, the transducer was placed at about 7.5 cm from the target i.e. a very short range in SONAR terms, useful, for example, for close SONAR inspection of a target with a miniature remotely operated vehicle.

In the present case, both the electronics and array were designed to fit within the 16 x 16 mm^2 footprint outlined previously but they have not yet been optimized in their depth dimension. Many connectors and cables were still used in the electronics block as it was only at its second stage of development. This involved power supply, connection to PC and instrumentation and to the transducers. These arrangements are clearly not optimum in terms of noise but the basic functionality of the system has been demonstrated, not least including the capability to use software to configure different excitation codes.

6 CONCLUSIONS

In this paper, the concept of the MOSAIC system has been introduced: MOSAIC can be seen as a modular system designed to provide the necessary flexibility to allow it to be used across a wide range of applications without incurring substantial custom design costs. The flexibility of the system can be expressed in terms of the array configuration (1D or 2D, or indeed a combination), the number of elements in the array, the choice of the aperture, and choice of the frequency of operation.

The designs of the electronics block and of the preliminary transducer arrays have also been outlined and preliminary results of short range pulse-echo tests have been presented. These demonstrate that sophisticated array electronics can fit within the footprint of a high frequency 16-element array and that signals with adequate SNR can be obtained, even with a tile which is not optimised for noise performance.

The range of the present system can be expanded simply by reconfiguring the software to provide a longer data acquisition window. If SNR becomes inadequate, then alterations in the coding, and potentially additional drive block components can be included. Further work will include such issues as estimating system electrical noise and demonstration of system performance via parameters including transmitting voltage response, receive voltage sensitivity and beam profiles.

7 ACKNOWLEDGEMENTS

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