# An Efficient 3-D Beamformer Implementation for Real-time 4-D Ultrasound Systems Deploying Planar Array Probes

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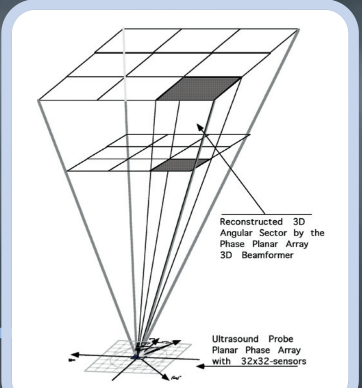
## Introduction

The computational intensity of the beamforming process required in 3-D and 4-D ultrasound systems is a major limitation in achieving real time system performance. The full 3-D beamformers require substantial processing power and are not inherently given to parallelization. In addition, memory requirements for beamformers are large.

The novelty of DRDC's decomposition approach reduces the 3-D beamformer into a simple efficient 2-stage line array process. The generic concept applies to all regular shaped 2-D or 3-D arrays. For example, a cylindrical array is decomposed into two stages of line arrays and circular arrays, and in the application of interest (a planar array), it is decomposed into two stages of line arrays.

The present work is part of DRDC's TIF Funding and the European Commission project ADUMS (IST-2001-34088) aimed at developing a fully-digital 4-D (3-D + time) ultrasound system for medical imaging applications.



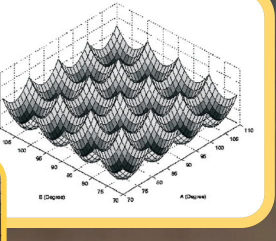
The 3-D Ultrasound System is composed of 5 major modules:

1. The data-acquisition and coded pulse transmission hardware
2. The 16 x 16 element planar array probe
3. The efficient softare implementation of the 3-D beamformer
4. A scalable multi-node PC cluster
5. 3-D visualization package

## Transmit Functionality

The transmit functionality is designed to illuminate the entire volume of interest with 9 (3 x 3) and up to 49 (7 x 7) firings.

Phased array illuminations and coding multiple frequency bands into a single pulse allows illuminiation of multiple focal depths with a single illumination.



The linearizing weighting function ensures uniform illumination across the volume of interest.

Energy distribution of a 7 x 7 illumination pattern with 2 focal depths.

## The Probe and Data Acquisition Unit

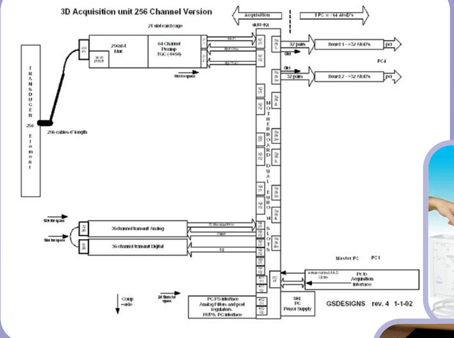
The illumination is done through 36 (6 x 6) elements and the RF signals are received by the full 256 (16 x 16) elements fo the planar phased array ultrasound probe.

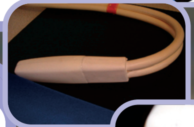
The required transmit patterns are preloaded into the memory of the unit.

The received data is delivered to the PCI bus of the nodes of the multi-node PC cluster.

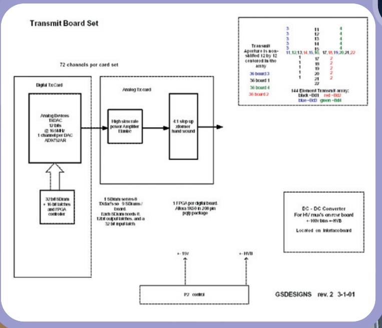
The Data-Acquisition unit is 64 channels, hence 4 firings are required to collect data for the full aperture.

### Receive Board Layout

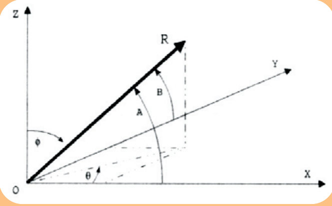




### Transmit Board Layout



### Definition of Parameters



The decomposition of the beamformer into a 2 stage process greatly reduced the complexity and simplified the parallelization operation.

## The Beamformer Implementation

The multi-dimensional beamformer for the planar array requires a 3-D steering vector that is defined by Equation 1:

$$B(f_i,A,B,R) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} X_{nm}(f_i)\text{-}S_{nm}(f_i,A,B,R) \qquad (1)$$

The steering vector, $S_{mn}(f_i,A,B,R)$ is expressed by the following equations:

$$S_{nm}(f_i,A,B,R) = \exp(j2\pi f_i \tau_{nm}(A,B,R))$$
$$\tau_{nm}(A,B,R) = \frac{\sqrt{R^2 + X_m^2 + Y_n^2 - 2x_m \cos A - 2y_n \cos B} - R}{c} \qquad (2)$$

The difference between the 3-D implementation and the efficient beamformer implementation is shown in Equation 3. Equation 2 is approximated to Equation 3, resulting in a simplified 2-stage implementation. For the element (m,n) in $(X_m Y_n)$, the exact beamforming delay $\tau_{nm}$ is approximated to Equation 3.

$$\tau_{nm}(A,B,R) = \frac{\sqrt{R^2 + X_m^2 - 2x_m R\cos A} - R}{c} + \frac{\sqrt{R^2 + y_n^2 - 2y_n R\cos B} - R}{c} \qquad (3)$$

The decomposition of the 3-D beamforming into two linear steps, is expressed as follows:

$$B(f_i,A,B,R) = \sum_{n=0}^{N-1} S_n(f_i,A,B,R) \cdot \left[\sum_{m=0}^{M-1} X_{mn}(f_i) \cdot S_m(f_i,A,R)\right] \qquad (4)$$

with the two separated steering vectors expressed as:

$$S_m(f_i,A,R) = \exp\left\{ j2\pi f_i \left( \frac{\sqrt{R^2 + X_m^2 - 2x_m R\cos A} - R}{c} \right) \right\}$$
$$S_n(f_i,B,R) = \exp\left\{ j2\pi f_i \left( \frac{\sqrt{R^2 + y_n^2 - 2y_n R\cos B} - R}{c} \right) \right\} \qquad (5)$$

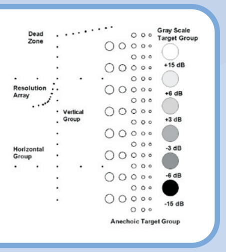
The summation in square brackets is equal to a line array beamformer along the X-axis. This term is a vector which can be denoted as $B_n(f_i,A,R)$. This can then be rewritten as follows:

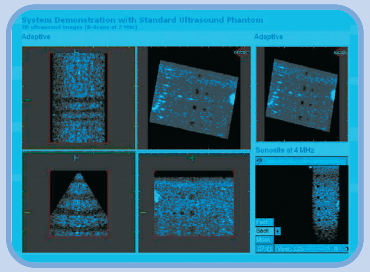
$$B(f_i,A,B,R) = \sum_{n=0}^{N-1} B_n(f_i,A,R) \cdot S_n(f_i,B,R) \qquad (6)$$

This expression is equal to a linear beamforming along the y-axis, with $B_n(f_i,A,R)$ as input. This 2 stage implementation is easily parallelized and implemented on a multi-node system.

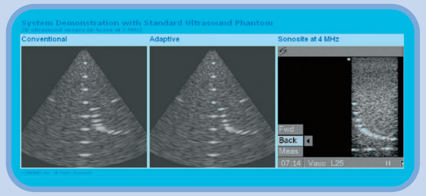
## Experimental Results

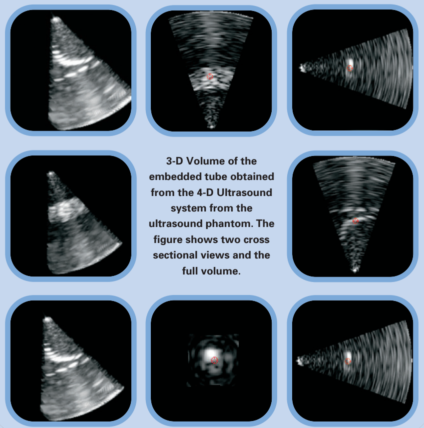
A standard ultrasound phantom is used in the experiments.





3-D Volume of the wire patterns obtained from the 4-D Ultrasound system from the ultrasound phantom. The figure shows the three cross sectional views and the full volume.

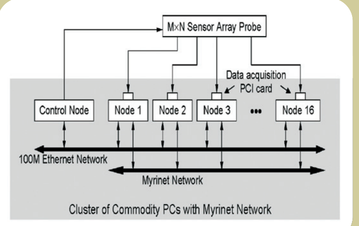




3-D Volume of the embedded tube obtained from the 4-D Ultrasound system from the ultrasound phantom. The figure shows two cross sectional views and the full volume.

## Multi-node Cluster

### Cluster of Commodity PCs with Myrinet Network



The beamformer is directly implemented into the processing cluster.

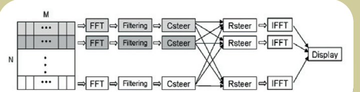
The multi-node cluster uses a high-speed fibre optic Myranet network.

The Cluster is constructed from commodity PCs.

The Cluster is fully scalable.

The Cluster is scalable, and supports high data throughput.

### Implementation



## Conclusion

This poster presents the components of a 4-D real-time ultrsound system, including the transmission functionality, the efficient 3-D beamformer implementation and the mapping of this beamformer to a multi-computer processing platform. Phased array transmission uses variable inter-element transmission delays to allow for full flexibility of energy focusing on space. In addition, multiple frequency regimes are coded within a transmission to enable the transmitted energy to be focused at multiple depths during a single firing by the system. The processing platform used is an 8-node cluster of commodity PCs. The mapping of the decomposed planar array beamformer to this type of processing structure is described.

System results from a 16 x 16 planar receiving array with a 6 x 6 transmit array are presented. Experiments have been carried out using a standard ultrasound phantom and the full volumes that are reconstructed from the beams generated by the beamformer are presented. Side-by-side comparisons of the full implementation 3-D beamformer and the proposed efficient implementation have been completed, showing no loss of performance by the proposed implementation. The results support the validity of the coded phased array energy transmission approach, the efficient real-time implementation of the 3-D beamformer, as well as the feasibility of the implementation of this beamforming on a parallel processing structure.

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