A HIGH RESOLUTION, REAL TIME 3D-ACOUSTICAL IMAGING SYSTEM

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1. INTRODUCTION

As a visualization tool on automotive controlled ROV's a real time acoustical imaging system provides a wider range of applications. However, the complexity of the system will increase with the required performance.
New processing algorithms have to be developed for beamforming and imageforming in parallel processing. The spatial Fourier domain is suitable for doing the real time focussing and the imaging.
Innovation in the design of a 2D-transducer array and the frontend electronics is necessary to be able to manufacture this system. The amount of data is increasing enormously by going to 3D-imaging. Flexibility in the processing hardware enables a reduction of dataflow by a user defined presentation of data.

Three-dimensional acoustical imaging provides opportunities for completely automotive operating of free moving vehicles in situations with poor visibility. Visualization in this and other hazardous environments requires a new generation of sonar systems. ROV's normally make use of optical or radar systems for tracking observation, classification and identification of targets (robotic imaging). On the one hand the various tasks of ROV's in this field of application will be inspection of offshore structures, seafloor survey and mine hunting. On the other hand applications with moving targets like tool manipulation do require the real time performance of the sonar system. An acoustical sensor should have comparable properties with respect to real time operation and field of view as optic systems. Furthermore, it should be multi-purpose to cover different applications and be robust in operation. However, attempts that have been made to develop a marketable 3D-acoustical imaging system have not been successful thus far. This challenge to innovation means a concentration of research forces in the field of transducer design, miniaturization and integration of micro-electronics, signal processing and system configuration. A feasibility study has been carried out to demonstrate 3D-image forming capabilities and to formulate the system requirements.

2. BACKGROUND OF 3D-ACOUSTICAL IMAGING

Basically, acoustical imaging is imaging of the reflectivity of the insonified volume. Reflectivity from scattering, reflection or even refraction depends on geometrical shape, surface properties and material of the targets. In contrast to optical imaging, mainly specular reflections will be obtained.

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This is due to the large wavelength with respect to the dimensions of the surface roughness. The need for high spatial resolution and high sidelobe suppression increases the complexity of the system considerably.

Before giving the requirements of the proposed imaging system a literature survey can give the state-of-the-art with respect to available techniques. Three different methods of acoustical imaging can be identified:

a. a linear or plane array with an acoustic lens for beamforming and focussing;
b. a phased array with beamforming by 'delay and sum' instrumentation or FFT-methods to resolve time delay,intensity and direction for a given reflection;
c. holographic methods where the image is reconstructed from received data in digital memory by making use of wave theory.

The first one is not practical in operation because of the rather fixed focal distance of the lens and is not flexible for various applications. Method c., mostly used in combination with synthetic aperture adopted from radar, is only of interest for applications with rather stable environments and targets. Combination of the processing of methods b. and c. in combination with real time acquisition could be used for image formation in the far field as well as in the very near field of the acoustical 2D-array.
The processing hardware and software will be based on a FFT-method for reasons of flexibility. In figure 1 a comparison is made between the optical and acoustical imaging, using plane wave decomposition.

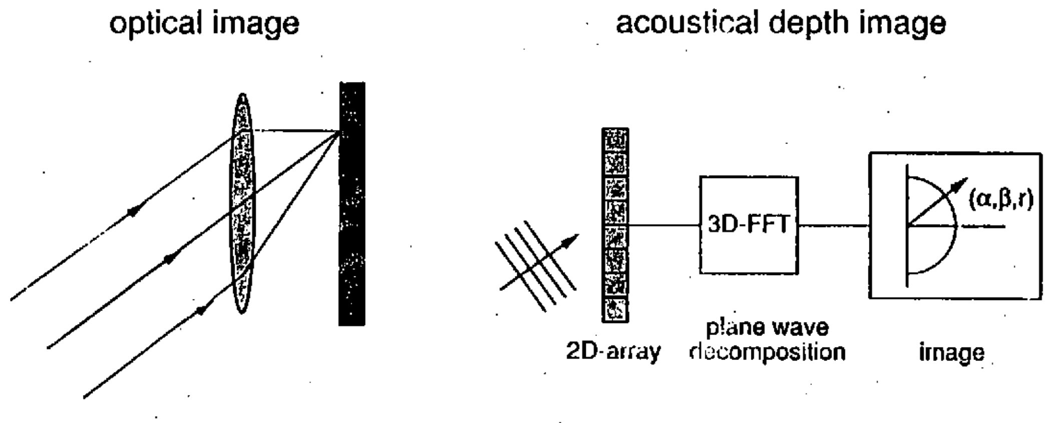

Fig.1: Imaging by an optical lens and by using a decomposition algorithm for acoustic plane waves reflected by a target in the far field.

3. SYSTEM SPECIFICATIONS

Requirements are primarily set by the angular resolution and the maximum detection range. In addition, the field of view, the real-time requirements and the backscattering function of targets are important. The final result of the image formation process will be a 5-dimensional vector space:

$$R(x,y,z,f,t)$$

The resolution first two lateral dimensions are given by beamwidth and focal distance (see eq.A1). The axial resolution in the depth field is depending on the frequency bandwidth of the signal. The last two dimensions are additional, not necessary for the volume imaging. The frequency dimension stands for multi-spectral operation where the image of the target is assumed to be different at different operating frequencies. The time dimension is the real time sequence of images which can be used for further processing.

The following user requirements for a wide range of applications are found to be adequate:

minimum voxelsize	: cm-range
measurement range	: 1-100 m
angular resolution	: $<$ 1 deg
field of view	: +/- 45 deg
frame repetition rate	: 0.1 sec
focal length	: 50% of the focal distance

The choice of frequency range is limited by the maximum detection range and by a high value of the scattering function of the target. The finest texture of flat surfaces like concrete structures or a seabed, have dimensions of 1 or 2 cm which leads to a wavelength in the mm-range. A transmission loss of 0.2 dB/m at 1 MHz sets the lower limit of the frequency range: 500kHz-1,2 MHz. With respect to signal-to-noise ratio the sonar-equation includes also the gain of the beamforming defined by lateral resolution and aperture width. For a symmetricly defined resolution cell (voxel) according to eq. A4 the frequency bandwidth is depending on aperture and range. This means that available bandwidth at large imaging distances can be used for frequency diversity.

For a fixed frame-rate there is a maximum range where real time definition is violated due to the movement of the target or the camera. The processing time per scan is also limited by the same time of flight as can be seen from eq. A5. However, electronical scanning in vertical direction and parallel processing can be used to fulfill the real time requirements.
Using these specifications in combination with the formula's in the appendix results in a list of design parameters:

number of elements	: 100x100
aperture dimensions of array	: .1 x .1 m^2
maximum frequency	: 1 MHz (wavelength=1.5 mm)
Specific for a target at 10 m	:
frequency bandwidth	: 1.5 %
range window	: 4.5 m (12000 samples)

Array configuration

In the field of underwater acoustics we do not have an equivalent for a CCD-array, which is a very efficient sensor for local light intensity distribution. Up to now we still need a complete circuitry for each single element to detect the local phase of the acoustical wave field. Innovative research will be needed on the integration of the transducer array with front-end electronics or to develop a new way of acoustic wave conversion.

Real time 3D-imaging for the given specifications requires a completely filled 2D-array which will have at least 10.000 elements. Basically the number of pixels in the frontal image is equal to the number of elements. The number of elements has to be minimized. The available space per transducer is not sufficient to contain all frontend electronics and the connections to the processing hardware. Up till now this problem can be dealt with by using scanning in vertical or horizontal direction. The reduction of elements can be obtained by building up the image by scanning the space in time. Scanning can be realized in two different ways:
- mechanical beamstearing of a vertical focussed detector array;
- mills cross array:
  . electronical beamstearing with vertical source array
  . detection with horizontal linear array.

A sparse filled array suffer from spatial aliasing and loss of resolution which is unacceptable with respect to specular reflections. Conditioning the source field by using special designed coded waveforms for adequate scanning can minimize these problems.

4. ALGORITHMS AND PROCESSING

A generic approach for acoustical imaging is adopted from seismics (see Berkhout (1) and Tatham (2)). A more detailed discussion of this theoretical background is given by Van Ruiten a.o.(3). The acoustic model for the experiment which describes the monochromatic response from targets at all depth levels at the detector array. In the simplified situation of backwards propagation in a homogeneous medium imaging can be presented in the Fourier domain.

Four major functions can be identified in data processing for 3D-imaging:

- pre-processing;
- beamforming in two dimensions;
- image forming;
- low level image processing.

The pre-processing step contains all actions to detect amplitude and phase of the wave field at every array position.
Conventional beamforming is a monochromatic process realized in dedicated hardware. By processing in the Fourier domain beamforming is equivalent to plane wave decomposition, which is obtained by 3D-Fourier transforms:

$$P(k_x,k_y,z_0,\omega) = \text{3D-FT}\{ p(x,y,z_0,t) \}$$

The direction of every monochromatic plane wave component from the insonified volume is known by the wave vector (k_x,k_y).
The image formation process will vary depending on the application respectively in the near or in the far field (see definition in the appendix).
Imaging in the near field is the inverse problem which can be expressed for a given depth level z_i by:

$$R(x,y,z_i) = \text{IFT}\ \Sigma_\omega\{ F^{-1}(k_x,k_y,z_i,\omega).P(k_x,k_y,z_0,\omega)\}$$

where IFT = the inverse Fourier transform,
P = the monochromatic sound pressure at the 2D-array in the Fourier domain,
F^{-1} = an inverse operator which describes the compensation for forward and backward wave field propagation.

The assumptions are made that transducers are omnidirectional and the source matrix has become a unit matrix.
Imaging in the far field is mapping of reflectivity in the spatial domain at the depth of the target plane just by geometrical conversions. The mapping concerns the process of calculation the angle components (p_x,p_y) by interpolation from the k_x,k_y,ω-domain according to:

$$p_x = k_x/\omega = \sin\alpha/c \quad \text{and} \quad p_y = k_y/\omega = \sin\beta/c$$

All frequency components for one angle (α,β) are gathered and inverse FFT results in:

$$p(\tau,\alpha,\beta) = \text{IFT}\{ P(\omega,\alpha,\beta) \}$$

where τ is the intercept time defined by $t=\tau+p_x x+p_y y$
After geometrical conversions the reflectivity of the volume is mapped in the spatial domain. This broadband technique is adopted from seismics and is called Tau-pi mapping (see Tatham (2)).
In fig. 2 these processing steps are illustrated.

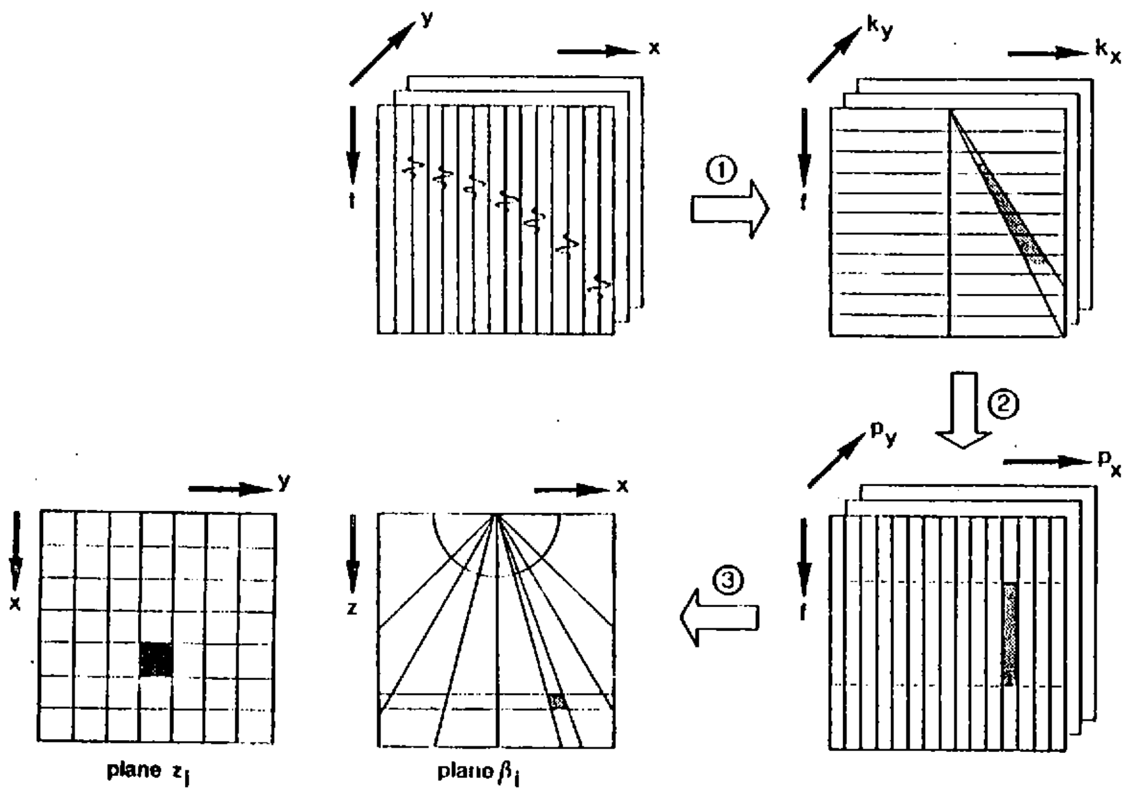

Fig. 2: Processing steps in imaging of broadband plane waves.
step 1: 3D-FT of array data p(x,y,t): in the near field focussing must be used before this step.
step 2: compensation of propagation by Tau-pie mapping
step 3: mapping of (p_x, p_y, f) to $R(x,y,z)$ or $R(x,\beta_i,z)$

The next possibility is extension of this method to the near field of the array. The Fraunhofer condition can be fullfilled by traveltime correction in the time traces along the array elements. This alignment step must be done before Tau-Pie mapping. The focal zone is limited in aperture angle, so the aligned data is only a portion of the total data. For imaging very close to the array, the holographic technique mentioned before can be used.

The basic idea is the data storage of a 'single shot' record at all the array elements. The preprocessing for every element must be minimized because of the large number of front-end IC's. Beamforming and imageforming in the horizontal directions can be processed in parallel. The total amount of dataflow after preprocessing is about 1 Gbyte/s.
Additional properties of an imaging system are relevant for the possibility of focussing, multi-spectral imaging and acoustic holography. These requirements are depending on flexibility in processing hardware. Only user selected and 2D-images are presented, which can mean data reduction before processing. Storing of 3D-data is only possible after data compression or data interpretation.

6. EVALUATION

Going from a linear array to a 2D-array with comparable resolution means an extrapolation of the number of components, the scale of integration and a number of processing operations which go beyond the feasibility with conventional beamforming techniques.

By using processing algorithms in the Fourier domain, which can operate in parallel and by using the flexibility of software to modify the system for various applications it will be feasible to meet the requirements. Flexibility in the system is given by the bandwidth of the signal. Bandwidth can be used for axial resolution, scanning during acquisition and multi-spectral operation with respect to reflection properties.

The large amount of data after the imaging process can not be presented in real time. Real time interpretation is necessary to use the benefits of a real time 3D-imaging system. Research on high level image processing like real time knowledge base systems, data fusion,etc. must lead to a new generation of vision systems.

APPENDIX

This appendix is a summing-up of formulas used in the fesaibility study.
The voxelsize is defined by angular resolution (see fig.1):

$$\Delta\alpha = \Delta\beta = \lambda/L$$

where L = length of the array(aperture width)
λ = wavelength

and axial resolution by:

$$\Delta r = 1.4\ c/B$$

where B = bandwidth

For a symmetrical voxel definition this leads to range depended bandwidth of the wavefield defined by:

$$B/f_0 > 1.4\ L/r\cos\alpha$$

where α = maximum angle of observation of the target
f_0 = frequency

The angular resolution is obtained by a linear array of length L. There is no spatial aliasing or grading lobe within the field of view for the number of elements defined by:

$$n > 2L.\sin \alpha_{max} / \lambda$$

where α is the maximum aperture angle.

The realtime definition sets constraints for the system design given by:

$$FR.r.N = c/2$$

where FR = number of frames per second
r = target distance, maximum depth range
N = number of scans per frame

The far field condition for a linear array is fulfilled for range:

$$R = 2L^2 / \lambda \quad \text{or} \quad R > 2L / \Delta\alpha$$

Higher resolution consequently means a larger near field which leads to focussing ability of the system.

REFERENCES

(1) A.J.Berkhout, "Seismic migration, imaging of acoustic energy by wave field extrapolation - A: Theoretical aspects", Elsevier Scientific Publ.Company, Amsterdam, 1982

(2) R.H.Tatham, "Multidimensional filtering of seismic data", Proceedings of the IEEE, October 1984

(3) C.J.M.van Ruiten, G.Boersma, A.J.Berkhout,"The state-of-the-art in real time 3D-acoustical imaging", Proceedings of Acoustical Imaging 18, 1989