CHAPTER 1

INTRODUCTION

Acoustic arrays are used for many imaging applications, including medical imaging, sonar, atmospheric imaging, seismic imaging, and nondestructive evaluation. Typically, one-dimensional arrays are used to collect data and two-dimensional images are formed, where the first dimension is azimuth and the second dimension is range. For medical imaging, extensions have been made to 1.5-dimensional arrays, which have many elements in the azimuthal direction and few elements in the elevation direction so that some focusing in elevation can be included. These 1.5-dimensional arrays are also used to form two-dimensional images.

Two-dimensional arrays, which allow focusing and beamsteering in both azimuth and elevation, are desirable in imaging applications because they offer the possibility of improved image quality for two-dimensional images or they can be used for three-dimensional imaging. Three-dimensional imaging allows better visualization of anatomy or structures. In medical imaging, three-dimensional images can provide information on the shape of a solid mass, one of the parameters used to distinguish benign and malignant tumors. Real-time three-dimensional imaging would allow a physician to view the structures of the heart throughout the cardiac cycle. In sonar, volumetric imaging is most often considered for short range applications (less than 10 m) such as fish counting, assisting divers, monitoring remotely operated vehicles, or mine hunting. Real-time three-dimensional imaging could provide the visibility required to locate objects such as damaged pipes in turbid water.

In seismic imaging or nondestructive evaluation, real-time implementation of three-dimensional imaging is not critical because the targets are stationary. However, for medical imaging, sonar, and atmospheric imaging, real-time data collection is important. Transient events might be missed if the time to scan the volume is long. Also, images created off-line would be distorted by motion of objects in the scene during data collection. The remainder of this thesis will focus on sonar and medical imaging.

1.1 Real-Time Three-Dimensional Ultrasound

Three-dimensional medical ultrasound exists; however, it is not real-time. Current systems typically scan two-dimensional planes using linear arrays and then translate or rotate the array to scan the next plane. Three-dimensional images are then formed off-line [1]. Often for cardiac imaging, where real-time data collection is most critical, data are collected over several heart beats, and then the data from differenct cycles are combined so that a single cycle of the heart can be recreated as a cineloop. Successive heart beats must be similar enough for the reconstruction. In many cases, irregular heart beats are thrown out [2], [3], making it impossible to use these systems to diagnose a heart abnormality.

Real-time three-dimensional imaging, meaning updating the volume of data at a rate of 30 Hz, is difficult due to two problems. The first is a problem only because of the current state of array fabrication technology. The second is a more fundamental constraint, dependent on the properties of the medium. Our study addresses the latter; however, it is worth mentioning the issues of array construction. Three-dimensional imaging requires a two-dimensional array. The difficulty in fabricating two-dimensional arrays arises from the large number of very small, very closely packed elements. A large number of elements is required to achieve a reasonable aperture size for resolution. Elements must be small and closely packed because a fully sampled array must have an interelement spacing of $\frac{\lambda}{2}$ or less in order to avoid grating lobes, where λ is the wavelength in the medium. For a system operating in water at 3 MHz, the wavelength is 500 μm. As frequency increases, the wavelength decreases, making the problem worse. Small elements can have poor sensitivity due to their high electrical impedance, and small elements make electrical connections difficult. Close spacing increases the potential for electrical or acoustic cross-talk. A large number of elements implies a high channel count, which is difficult to implement due to space limitations. The number of elements can be reduced and the interelement spacing increased by using sparse array layouts [4], although reducing the number of elements will increase the average sidelobe level of the beam pattern. The sensitivity, cross-talk, and connection problems can be addressed using new technology such as thick films, although much improvement is still needed [5], [6], [7].

The second challenge in implementing real-time volumetric imaging systems is the slow speed of data collection. Data collection for a three-dimensional image using techniques of two-dimensional imaging requires too much time for volumes to be scanned in real-time. The physical limit is the speed of sound in the medium. For example, collecting data for a medical image up to 15 cm deep in the body requires 25 ms, where the speed of sound is assumed to be 1540 m/s and where 128 pulses are used to create 128 lines in the image. A three-dimensional image formed with 128^2 pulses under the same conditions requires 3.19 s. Real-time three-dimensional imaging using conventional data collection techniques would be impossible. The solution to this problem is to form several beams from one transmitted pulse and to separate reflections from different directions through processing.

1.1.1 Medical imaging

Several groups have developed methods for real-time three-dimensional medical imaging. Using a sparse synthetic aperture beamformer, Lockwood, Talman, and Brunke [8] have developed a linear array that is mechanically rocked to collect data for three-dimensional images. The system is a modification of currently available systems that rock the transducer to collect a volume of data in that the rocking is accomplished at a high enough rate for the data collection to be real-time. Few transmit pulses, each using a small number of elements, are used to reduce the data acquisition time for a single transducer position. With synthetic aperture beamforming, all the receive beams corresponding to one transmit pulse can be formed simultaneously. Using a linear array reduces the required channel count. This technique has been demonstrated for medical imaging only in simulation.

Shen and Ebbini [9] have worked on coded-excitation in combination with a pseudo-inverse operator so that multiple beams can be received at one time. This system has been tested for two-dimensional image creation using a one-dimensional array. Independent codes are transmitted on each element, resulting in different impulse responses in each steering direction. Returns from different directions are then separated using filters. Their proposed method does not require a Nyquist sampled array, so that fewer elements of the two-dimensional array may be used without degrading the image quality. Images formed using previous coded-excitation methods with matched filter operators have suffered because correlations between beams in different directions produce artifacts in the images. Shen and Ebbini's technique is reported not to have this drawback; however, the pseudo-inverse operator suffers from consequences of the assumption that targets occur on a grid pattern. If target positions differ from the grid pattern, the image quality is degraded.

Lu [10] has proposed a technique for three-dimensional imaging using limited diffraction beams. In this case, a plane wave pulse is transmitted from the two-dimensional array to illuminate the scene. Then in reception the same transducer array is used to form an array of diffraction limited beams by varying the weighting on the elements. Using a three-dimensional inverse Fourier transform, a three-dimensional image is created. This technique requires a fairly large, broadband array, and it is limited to imaging the region directly in front of the array. The largest cross-sectional area that can be imaged is equal to the area of the array. The imaged area can be increased only by using a large number of transmit pulses. The method has been tested using a phantom with embedded point scatterers [11]. The results look promising, although the images reveal the dependence of the technique on the broad bandwidth of the transducer.

Finally, researchers from Duke University have a real-time volumetric imaging system, which is in operation [12]. Their system uses a sparse, two-dimensional array. As reported in 1991, the volume is scanned in a pyramidal scheme, with 12 transmit pulses in the elevation direction and 52 transmit pulses in the azimuthal direction, for a total of 624 transmit pulses per volume. Parallel beamforming is used in the elevation direction so that eight receive beams are formed for each transmit pulse. The volume can be scanned eight times per second. Initial image quality was poor. To improve the image quality, they have been working on improving the two-dimensional array, increasing channel count and frequency. They would also like to implement parallel beamforming in the azimuthal direction as well as in elevation.

Although many groups have been working on the problem in medical imaging, the ideal solution has not yet been found. Shen and Ebbini's technique has not yet been extended to volumetric imaging. Lu's technique is promising; however, to achieve the high frame rate, it requires that signals received by every element be stored, which means having a large number of channels. As explained earlier, having a large number of channels is difficult due to space considerations. The synthetic aperture methods of Lockwood and Smith are fairly brute force methods to reduce the number of transmit pulses used. The frame rate on the Duke system was 8 frames/s. In order to increase the frame rate, the number of transmits will have to be reduced even further.

1.1.2 Sonar imaging

Three-dimensional sonar imaging has been developed for applications such as fish counting, mine hunting, and inspecting structures. In general, systems are designed to complement or replace optical systems, which are ineffective in turbid water. Sonar imaging differs from medical imaging in the ranges of interest. Maximum ranges of interest range from 170 m to 2.4 m, and operating frequencies range from 200 kHz to 3.5 MHz. In order to accomplish real-time sonar imaging, even fewer transmit pulses are available than for medical imaging. Several of the systems discussed in the literature are based on transmitting a single pulse with a broad region of coverage and then focusing or processing the received signals to produce an image. Jones [13] uses the simplest system, transmitting a chirp over a broad region and then using a sparse two-dimensional array to steer and focus the receive beam. Such a system will suffer from poor signal-to-noise ratio due to the broad spread of energy in the transmit and the high average sidelobe level of the receive beam pattern. Also, the broad transmit beam will lower the achievable resolution.

In [14], a single transmit is used to insonify a region and a two-dimensional transducer array is used to receive reflected signals; however, the processing is not the same as conventional beamforming of the received signals. Instead, the processing uses a noncoherent correlation of the received signals, or correlation of the envelopes of the received signals. First, the magnitude-squared of the received signal from each element is calculated. Each of these detected signals is multiplied by the envelope of the transmitted signal appropriately delayed to correspond to the location of a reflector at the assumed angle and range. The multiplied signal is then integrated, and the sum over all the array elements is taken. A large sum indicates a target at the assumed direction and range. The proposed method is reported to have the advantages of no grating lobes regardless of interelement spacing and reduction in speckle. However, it is acknowledged that the method will have poor angular resolution. In fact, both angular resolution and depth of field depend directly on ct_e/f_0, where c is the speed of sound, t_e is the time duration of the transmitted signal envelope, and f_0 is the carrier frequency. Angular resolution is also inversely proportional to the size of the array. Since small angular resolution and large depth of field are desirable, the best way to improve angular resolution is by increasing the size of the array; however, total array sizes are generally limited. For example, in a diver held sonar, the array must fit into a system that a diver can hold. In addition, although -3 dB beamwidth of the correlation system can be made comparable to that of a focused beamforming system, the -10 dB and -20 dB beamwidths of the correlation system are much larger than those of the focused beamforming system, meaning poor image contrast. This system has been demonstrated in simulation for three-dimensional imaging of few point targets.

Ishihara et al. have developed a system that uses a coded wavefront [15]. As discussed earlier, coded wavefront systems suffer from image artifacts due to the non-orthogonality of beams in different directions. Here, multiple transmits and receptions are used to compensate for this problem. As presented, the maximum range tested is 170 m. Collecting data for and reconstructing one image requires approximately one second. For much shorter ranges, reconstructing an image would require less time; however, the requirement for multiple transmit pulses limits the maximum achievable frame rate.

Other researchers are developing lens-based systems. Belcher et al. [16] and Kamgar-Parsi et al. [17] have developed three small, high-frequency sonars that use lenses. In both cases, the transmitter is a single element or row of the two-dimensional array. The receiver is the two-dimensional array located in the focal plane of the lens. An acoustic camera is being developed by Erikson at Lockheed Martin. It is also a lens-based system using a transducer hybrid array (THA) and a C-scan format for data collection [18]. A separate transmitter, with a wide beam, is used to insonify the region of interest. Then, an acoustic lens is used to image multiple planes onto the acoustic array. In all of these systems, the lens accomplishes the focusing, so that the electronics requirement is reduced. A small number of range planes can be collected with a single transmit pulse; more range planes are collected with successive pulses. The total range depth that can be imaged is determined by the depth of focus of the acoustic lens, which is limited. The design range for Erikson's system is approximately 120 mm, much shorter than our intended range. The maximum range is limited by the fact that multiple transmit pulses are required to collect the entire volume of data.

The systems mentioned in this section all use a transmit pulse with broad coverage. Resolution would be improved if the transmitted beam could be focused or made narrow in multiple directions.

1.2 Spatial Frequency Separation

Another approach to achieving multiple beams with one transmit pulse is to steer the beam by changing the frequency. F. L. Lizzi and K. W. Weil hold a patent on a transducer device which uses change in frequency to steer a beam [19]. Using a curved transducer with tapered thickness and then exciting the transducer with different frequencies, beams with different origins and steering directions can be radiated. By changing the frequency continuously, the beam is scanned through a sector. The system is limited by the fact that the ratio of highest to lowest excitation frequency cannot be more than three. Otherwise, at the highest frequencies, multiple beams will be radiated with different orientations and steering directions, as the transducer will radiate from all places where the excitation frequency is an odd multiple of a half wavelength of thickness.

This thesis presents the use of spatial frequency separation achieved using amplitude-weighting to solve the problem of slow data collection. The concept of steering the maximum response of an array using amplitude weighting was introduced by Hughes and Thompson in 1976 [20]. At that time, the intent of amplitude steering was to tilt the maximum response of the beam pattern without using multiple delay lines or phase-shift networks, which are bulky. In their formulation, the beam was steered to a particular direction at a single frequency, and the fact that the steering direction changed with frequency was considered a drawback of the design.

By operating a linear amplitude-steered array in broadband mode, with an impulsive or chirp excitation, the maximum array response is swept over a range of angles. A sector can be scanned using a single transmit pulse, leading to fast two-dimensional imaging of the sector, compared to conventional imaging which uses one transmit pulse for each steering direction. The two-dimensional amplitude-steered array (patent pending), which can be used for volumetric imaging, uses frequency separation to determine vertical position and conventional beamforming to determine horizontal location. Although the array may be a fully sampled two-dimensional array, a separate channel is not required for each element. Only four channels are required per column of elements. Potential advantages of using this array for volumetric imaging are fewer electronics than required for proposed medical systems that must address each element individually and better resolution than current sonar systems that use a broad transmit beam.

1.3 Organization of This Thesis

This research was undertaken as part of a larger project developed by the Applied Research Laboratory (ARL) at the Pennsylvania State University. The team at ARL was led by W. Jack Hughes and Charles Allen. Other subcontractors include Northrup Grumman, Blatek, Inc., and TRS Ceramics, Inc., whose responsibilities were issues of array construction. This thesis is a study of the operation of the amplitude-steered array for imaging. Although we focus on an underwater imaging application, the array may be modified for use in other systems, such as medical imaging systems.

Chapter 2 introduces the amplitude-steered array by examining fundamental issues of how the linear amplitude-steered array would be used to form two-dimensional images. In particular, we study the tradeoff between axial and lateral resolution, and we survey various forms of time-frequency processing to form images. Chapter 3 discusses the extension of the linear array to a two-dimensional array for volumetric imaging. As presented, the array is a linear amplitude-steered array in one direction, and a conventional phased array in the perpendicular direction. A specific application is chosen around which a specific array is designed. The array layout is discussed along with the achievable resolution. Finally, strategies for presenting images from the data are given, including surface rendering, slice images, and projection images. The analyses in Chapters 2 and 3 are performed with simulated data. In Chapter 4, we compare simulated results to experimental data collected with a low frequency version of the linear amplitude-steered array. Having validated the simulations with experimental data, we show the effect of nonlinear propagation on the operation of the array in Chapter 5. Nonlinear propagation results in the generation of higher harmonics, and our processing equates frequency with position. Therefore, we must consider the possibility that false targets will appear in the images. Finally, Chapter 6 gives a summary of research results and suggestions for future work.