AN ULTRASONIC SENSOR FOR CLOSE RANGE COLLISION AVOIDANCE ON AUVS

Seán Nolan and Daniel Toal

Mobile and Marine Robotics Research Group,
University of Limerick, ireland

Abstract: This paper presents work on the experimentation and testing of an ultrasonic collision avoidance sensor for use in proximity to the seafloor or other hazards. A single beam single frequency transducer is utilised to achieve a wide-angled beam profile at short wavelengths. This is realised through the use of a curved piezoceramic element in the transducer design. With centimetre range resolution and an extremely small dead zone, a low-cost sensor with fast response is achieved.

Keywords: AUV, curved radiator, sonar, ultrasonic, collision avoidance sensor, sonar, short range, guidance, trilateration, triangulation.

1. INTRODUCTION

A vital component of any unmanned underwater vehicle is a means of obstacle or hazard detection and although considerable advances have been made in the realm of underwater vision systems, sonar has remained the practical solution to this problem. There are a host of collision/obstacle avoidance sonars (CAS/OASs) available commercially and these vary greatly in sophistication and cost. The simplest of these systems comprise chains of sonar altimeters and can be used to detect the presence and range of large obstacles around a craft but provide only range to target information. These are at the low cost end of the spectrum. Another common solution, used widely on remotely operated vehicles (ROVs), is the mechanically scanning Imaging sonar. This type of system can typically deliver range and bearing information to target but is limited in that it cannot unambiguously determine target altitude or distinguish between targets at different altitudes with the same range and bearing (Enfang, Longbin et al. 2000). At the top end of the scale is the forward-looking sonar (FLS). Several variations of forward looking sonar exist; among them FLSs using analogue and digital beamforming and continuous time frequency modulated CTFM techniques. They can be broadly characterized as utilizing multi-element, phased arrays and signal processing techniques to electronically scan a sector of terrain generally in the vehicle's forward path (Loggins 2001). FLS represents the state of the art in commercial OAS technology and is superior to other types of commercial OAS in both data resolution and update rate. In an AUV context, (Martin, An et al. 2000) describes an FLS integrated as a CAS on the Morpheous AUV. However, most FLSs feature multi-element send and/or receive arrays, which are by nature bulky components (Enfang, Longbin et al. 2000; Martin, An et al. 2000; Loggins 2001), feasible on larger research AUVs, with sizeable onboard power reserves. Typically, such vehicles are flown in mid-water well away from sea floor hazards and potential obstacles. For an untethered unpiloted AUV, power consumption is a constraint and an OAS must provide spatial information on the underwater environment, through an interface to the guidance and control subsystem of the vehicle (Shaw 1990). On the whole, commercial OASs require extensive modification before they can be integrated on an AUV, are designed to operate at detection ranges greater than 2m, and typically have range resolution between 5cm and 1m (Loggins 2001). Furthermore, with currently available data processing methods, performing 'real-time' object classification on the output from a state-of-the-art OAS such as forward looking sonars is a significant challenge.

If AUVs are to be used in an intervention role close to underwater hazards then the aforementioned attributes are inadequate. To address these stated shortcomings a different approach to OAS design must be adopted. Any sensor system designed for an AUV must be compact because the dry-hull /payload space available onboard an AUV is limited (Ishoy 2000) and hence, the authors propose the use a number of smaller sensors that operate independently or co-operatively to detect hazards in the AUVs work envelope. These could be more easily mounted than a bulky array on smaller vehicles and unlike available sonars would have a wide-angle field of view, a short (2 cm to 2m) detection range with range resolution of ≤1 cm, and fast response time, making AUV servoing possible. In this paper work on a wideangle ultrasonic transducer with good range resolution is presented and a detection scheme for localizing target position in 3 dimensional space using trilateration methods is described.

2. SENSOR DESIGN

2.1 Sound Characteristics of Piezo Elements.

For a thickness mode piezoceramic, its natural resonance frequency is related to its thickness dimension and its characteristic sound radiation pattern is related to its lateral dimensions; length and width in the case of a rectangular block shaped piezo and diameter in the case of a cylindrical disk. Since piezoceramics have the property of reciprocity, the transmit and receive radiation pattern of a given transducer are the same. The directivity of a thickness mode piezo electric radiator is a function of the surface area of the transducer and the operating frequency (Krautkramer and Krautkramer 1990). The directivity for a flat disk shaped piezoceramic at an angle α is given in (4.1).

$$D(\alpha) = \frac{2CJ_1\left(\frac{2\pi rf \sin \alpha}{C}\right)}{\pi fd \sin \alpha} \tag{1}$$

where, D(α) is the sound pressure at angle α, C indicates the speed of sound in water, J_1 is a Bessel function of the first kind, f represents frequency, d denotes piezoceramic diameter and the r = d/2. From equation (1), we can see that beam width is inversely proportional to both frequency and ceramic diameter. In order to increase the beam width of a disk shaped piezo, either the wavelength λ or the diameter d must be decreased. As previously stated, a sensor system using short wavelength with high range resolution is required in order to realize a sensor design that can operate in the proximal range (2cm to 2m) and also satisfy the requirement for a compact sensor head design. Since the operating frequency must be high to yield a short wavelength then only the piezo diameter can be reduced. However, to do so is impractical for a number of reasons:

1. When piezoceramic diameter is reduced transducer sensitivity is reduced.
2. In a thickness mode transducer unwanted resonance modes can appear near the resonance frequency as diameter d is decreased in width toward the piezo thickness t.

Widening the beam angle in any case means that the beam energy is spread over a wider area and so the intensity at any given point in the widened beam envelope is reduced. It is therefore imperative that the largest possible radiating area be utilized to transmit energy from the resonating piezo into the water. At frequencies above 1MHz, flat rectangular or disk shaped piezo elements are unsuitable for use in the design of a wide-angle directivity transducer. However, a transducer with a convex radiation surface which will radiate a short sound impulse into a wide area.

2.2 Transducer with Convex Radiation Surface.

It can be shown that the sound field radiated in a given direction by a spherically curved antenna is mostly radiated by an angular sector of the circumference corresponding to the first fresnel zone (Lurton 2002). The angular extension of this fresnel zone is given in equation 2.

$$\gamma_F = 2\sqrt{\frac{\lambda}{\rho_c}} \tag{2}$$

where ρ_c is the radius of antenna curvature, and λ is wavelength. If γ_F is small relative to the angular extension γ_c of the entire antenna, the directivity pattern is close to the geometric aperture of the physical antenna. The design of a convex transducer is shown in figure 1. Its fundamental frequency is 2 MHz and it has a main lobe width in the order of +/- 14 degrees at -3dB. The physical dimensions of the piezo are given in Fig. 1; piezoceramic thickness was 1mm.

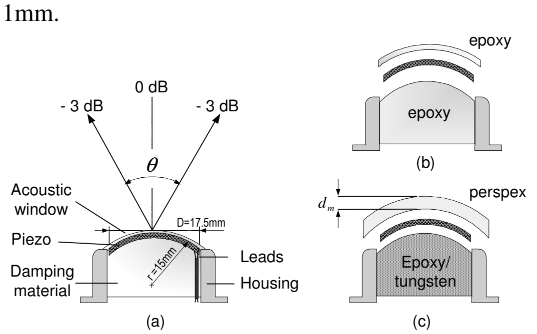

Fig. 1. Design and construction methods of a convex transducer.

<u>Active Element</u>

The piezo used was a Pz26, lead zirconate titanate (PZT), commercial focusing-bowl manufactured by Ferroperm Piezoceramics A/S. The Pz26 ceramic material is typically used in underwater applications and exhibits a high mechanical factor (Qm) and low dielectric loss. The piezo element was polarized for use in the thickness mode of oscillation and designed to resonate at a single frequency, having a narrow bandwidth.

Backing material

Several materials including Silicon and Urethane rubbers as well as Teflon and Epoxy were evaluated as possible candidates for the transducer backing. The level of damping provided by Silicon and urethane was insufficient. Teflon, while having desirable acoustic damping qualities proved difficult to bond to the back of the curved piezo. A two part epoxy was chosen for ease of fabrication, see figure 1b.However, the acoustic impedance of epoxy is not close to that of the piezo so results are not ideal. A highly attenuation, high density material is necessary to reduce excessive 'ringing' during transmission. In figure 1b an alternative backing is proposed using an epoxy filled with tungsten powder. This will result in a more heavily damped transducer. Consequently, the distortions in the far field sound distribution shown in figure 2 and 3 (for short transmission pulses) will be reduced.

Acoustic Window

In the fabrication of the prototype of figure1b, a very thin (<< λ/4 thickness) matching layer of epoxy has been applied to the face of the transducer to form an acoustic window and protect the piezo. Epoxy has a high sound speed relative to water but is suitable for use at frequencies above 1MHz. An improvement in acoustic window, design is now being implemented. As shown in figure 1c, a matched layer window is being precision machined from Perspex which has an acoustic-impedance between that of the piezo and water. The window thickness is related to a quarter wavelength of sound in Perspex by equation (3).

$$d_m = 2(n+1)\frac{\lambda}{4} \quad (3)$$

where n is a multiple of layer thickness and λ_p is the wavelength of sound in perspex.

Electrical matching

The electrical parameters of the transducer are influenced by both mechanical factors such as the window material and level of damping, and electrical factors such as the electrical capacitance of the transducer and its electrical termination. With the transducer immersed in water the electrical parameters of a prototype transducer, including coaxial cabling and BNC connector, were measured using an Impedance/Gain-phase analyzer (Hewlett Packard 4194A). The peak impedance magnitude occurred at a frequency of 2.25 MHz and had a magnitude of 65.9 ohms with -48 degrees phase. The peak admittance of the prototype at anti-resonance was measured at a frequency of 1.86 MHz and had a magnitude of 39mS and 46 degrees phase. Additional components were not required for electrical matching.

3. MEASUREMENT AND TESTING

3.1 Equipment Setup.

Transducer gain profile was measured using a PVDF needle hydrophone. The test setup is shown in the block diagram of figure 2. Both the transducer and hydrophone were immersed in water. The transducer was mounted in a tailor made assembly located on the end of a high accuracy robot arm. Movement of the arm was controlled by a LabView program which was also used to log sample data and position information at each sequential step. A second measurement setup shown in figure 3 was used to measure reflections off selected targets. In this case the position of the transducer under test was kept fixed and a motorized scanner was used to adjust the range of the targets from the transducer. Here the transducer was operated as a transceiver. As before movement and sample logging was carried out using a LabView program. Signal transmission and reception was carried out using a DSP module with channel multiplexing.

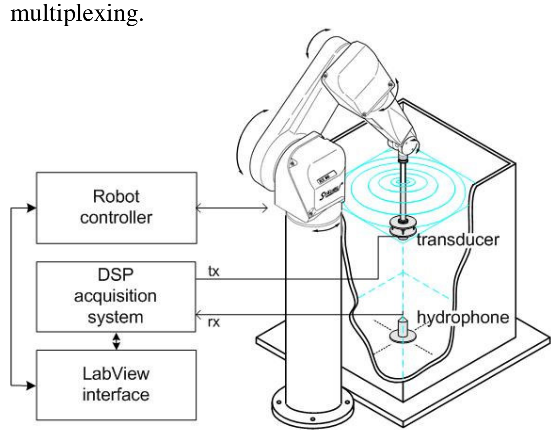

Fig. 2. Block diagram of robot test system used to measure sound pressure distribution and directivity of transducer.

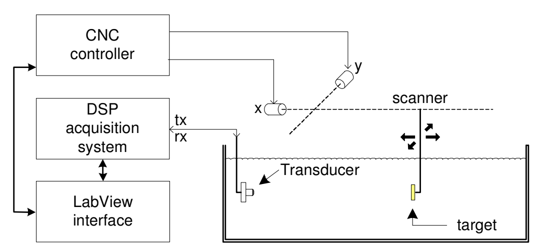

Fig. 3. Block diagram of test setup used to measure reflection off known targets over distance.

3.1 Directivity Pattern

Figure 4 shows a measured impulse from the curved transducer at a point on the centre axis, 30 mm from the radiating face. The time between samples Δt = 25nS. From this measurement, the number of cycles and the phase shift in the signal indicate that the transducer is not heavily damped and that there are possible reflections present from the backing material or indeed the acoustic window.

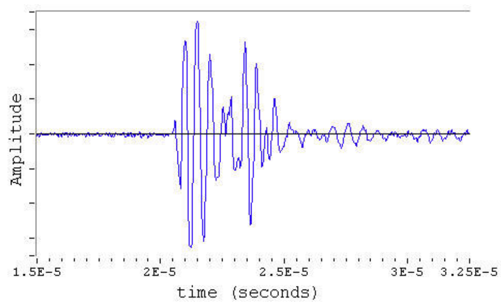

Fig. 4. Received sound impulse measured on centre axis, 50 mm from face of convex transducer.

The sound pressure profile for a flat disk transducer and the prototype curved transducer with the same surface area were measured for comparison. Transducers were excited with a single half cycle positive going pulse. The step size between sequential measurement positions was 1mm and the total width of the scan was 275mm. For each of the curves shown in figure 5, measured data was normalized relative to the peak response of the transducer under test. We can see from the plots of figure 3 that the beam profile produced by the curved element transducer is much wider than that of a flat element transducer of similar thickness and diameter. At -3dB the flat element transducer has a beam angle of 8 degrees while the curved element transducer has a beam angle of approximately 28. However, the figure 5 plot for the curved transducer shows reveals undesirable fluctuation in the sound pressure across the sound field and in particular a 7dB minima which occurs close to 0 degrees.

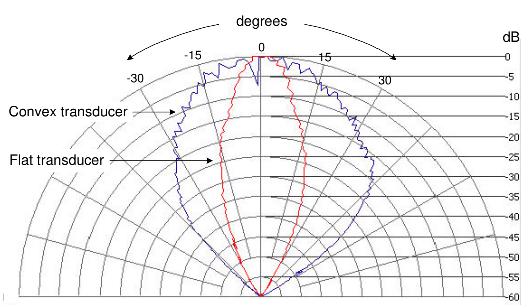

Fig. 5. The directivity measured for a convex transducer and a flat circular transducer of the same radiating surface area.

3.2 Target Response

Tests were conducted with various sizes of flat disk and spherical reflector and the results with flat and curved transducers recorded. The step distance between successive measurements used was 2.5mm. As in the technique used for gain profile measurement, the receiver gain was adjusted at each new step so that the received signal amplitude remained constant over distance. In the plot of figure 6, the difference in reflection amplitude from a disk reflector for a flat transducer and curved transducer can be observed. As range increases the measured reflections for the curved and flat transducers converge. While at close range the more focused beam of the flat transducer results in approximately 10dB higher reflection for each diameter reflector. At larger ranges however with beam divergence this disparity is less pronounced. From the results plotted in figure 7, the effect of a reduction in sphere size on reflected signal can be observed for a curved transducer. The targets used were made of steel. With spherical reflectors, the orientation of the sphere relative to the transducer does not affect the level of reflected energy and so reflector alignment is not as critical. The effective reflective area of a sphere is determined by sphere curvature and hence the reflected signal from a sphere is much less than that reflected from a flat disk of the same diameter. There is approximately 10dB of a reduction in reflected signal between a sphere of 28mm and 12mm diameter at any given distance.

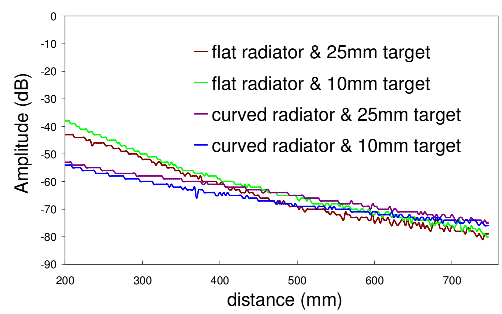

Fig. 6. Reflection from different sized brass disks with increasing range measured with a convex transducer.

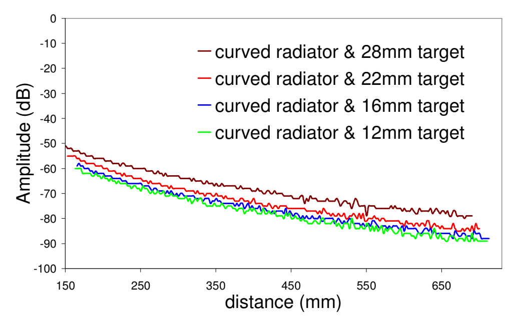

Fig. 7. Reflection from different sized brass spheres with increasing range measured with a convex transducer.

Figure 8 shows the results of testing performed to compare the acoustic response of a curved transducer at a 30-degree angle off its symmetrical axis to the acoustic response of the same transducer centred at 0 degrees on the same axis. The reflector used was a brass disk of 25mm diameter. For this test the flat disk was oriented to achieve maximum reflection and target range was increased with bearing fixed. At increased angles of bearing, the amplitude of reflected signal over distance for a given size target is reduced because of the characteristic beam directivity of the transducer. In figure 8 a 12dB increase in attenuation in the 30-degree plot relative to the 0-degree plot can be observed.

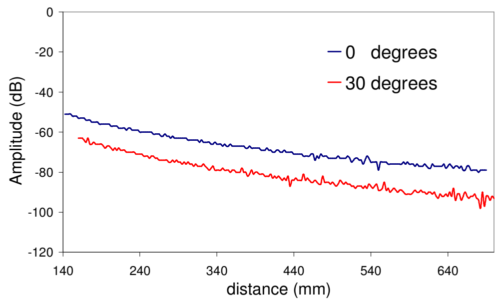

Fig. 8. Measured reflection from a 25 mm brass sphere reflector with increasing range for a convex transducer (1) with the reflector moved along an axis centred in the direction of sound propagation, the central axis and (2) with the reflector moved along an axis at 30° to the central axis.

Range resolution is defined as half the minimum distance for which a change in time of flight for a reflected signal can be discerned. In the tests conducted the value determined for range resolution of the prototype curved transducer was in the order of millimetres.

4. PROPOSED OAS DESIGN

4.1 Operating Principle.

Using multiple sensors an OAS can be realized for proximal detection and localization of targets. In the simplest form, the proposed OAS system comprises three transducers with identical wideangle detection cones. The three transducers are arranged in a triangular configuration at equal distances apart in a plane perpendicular to the direction of detection such that equal area from the three detection cones overlap. The idea is shown schematically in figure. 9. Three transducers have three detection cones, beam a, b, and c. The central region in the diagram, labeled 'a ∩ b ∩ c', denotes the zone where these beams overlap.

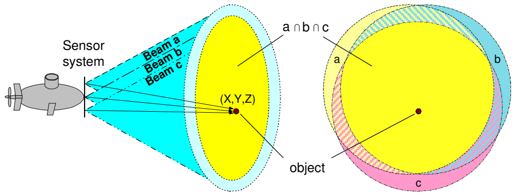

Fig. 9. AUV sensing approach using overlapping sensor beams to determine object position.

Many sensor configurations are possible including configurations where a fourth centrally located sensor is used as a transmitter and three sensors are used as receivers etc. but the configuration illustrated assumes that three sensors are used and that they are used as transceivers. In the diagram of figure 9, the region of intersection denotes where the detection cones of the sensors overlap an object can be detected by all three sensors. The distance between each sensor and the target can be derived from the measured round-trip time-of-flight from when a signal is transmitted, reflected by the target and received again. These three distance measurements can be used together with the known distances between the sensors to calculate the x, y, z position of the object relative to the sensor system by means of trilateration. Trilateration is a method to determine the position of an object based on simultaneous range measurements from three stations located at known sites. It can be trivially expressed as the problem of finding the intersection of three spheres; solving the following system of quadratic equations:

$$\begin{aligned} l_1^2 &= (x-x1)^2 + (y-y1)^2 + (z-z1)^2 \\ l_2^2 &= (x-x2)^2 + (y-y2)^2 + (z-z2)^2 \\ l_3^2 &= (x-x3)^2 + (y-y3)^2 + (z-z3)^2 \end{aligned} \qquad (4)$$

where, $p_i = (x_i, y_i, z_i)$ for i = 1,2,3, are the the coordinates of station of i, and l_i the range measurement associated with it. It is a common operation used in robot localization, kinematics, aeronautics, crystallography, and computer graphics (Tonshoff, Bedhief et al. 2000; Bank 2002; Thomas and Ros 2005). Assuming that a curve for the attenuation of the transmitted ultrasound in water is known the receiver gain can be adjusted (with time varying gain) so that the amplitude of a reflection for a given sized target remains constant irrespective of the target range. The resolution of the system is governed by the sensor wavelength λ in water. The wavelength is related to the speed of sound in water C and sensor resonance frequency f by the relationship λ = c/f. When higher frequency transducers are used the wavelength decreases, resolution increases and the minimum distance between transducers can be reduced leading to a more compact sensor head design.

4.2 Trilateration Algorithms.

The authors have implemented two general algorithms for trilateration. The first is based on a classic geometric formulation whereby the position of an object in 3D space is defined in terms of three reference points in the Cartesian coordinate system. The second algorithm implemented avoids the direct algebrization of the problem has also been implemented. This second formulation proposed by (Thomas and Ros 2005) uses a coordinate free (barycentric) coordinate formula containing Cayley-Menger determinants which have a geometric interpretation in terms of squared volumes, areas and lengths. In tank testing, both approaches proved equally accurate at determining target position. The second algorithm is the method preferred by the authors because target location coordinates appear explicitly as vectors allowing a simpler analysis of the effects caused by errors near singularities.

5. FURTHER WORK

Work is ongoing on sensor improvement and algorithm development. With respect to the transducer a new backing material consisting of a fine tungsten powder filled epoxy and a new precision machined acoustic window has been fabricated. The effects of both these sensor modifications are currently under test. Ways to improve the shape of the transducer beam profile and improve the range are also being researched. To counteract the higher sound attenuation at the 2MHz operating frequency the use of time varying gain TVG with received signals, a well-known technique from ultrasonic materials testing will be implemented. Further work will include integrating a number of sensors into an overall OAS system. Flexible send and receive electronics will be built to allow experimentation with different send receive configurations and detection algorithms. The system will then be integrated on a miniature autonomous underwater vehicle for experimental trials.

5. CONCLUSIONS

This paper has presented a wide angled transducer for use in the design of a low-cost OAS system. Such an OAS system is a key requirement of an inspection class AUV. The transducer design incorporates a single convex element piezoceramic and prototype sensors were of small size and power consumption. The directivity and sound pressure distribution of the curved transducer design were measured in water and compared to those of a flat circular design of similar dimensions. Both transducers had a 2MHz operating frequency. The measurements showed that despite the large vibration surface the convex transducer yielded an increase in directivity threefold that of the flat circular transducer. In tests the resolution of the sensor with a 0.75mm wavelength in water was used with short transmission pulses to detect a range of targets at close, down to centimetre, range. Attenuation over the short ranges measured was high due to the wide directivity pattern of the transducer but at the short detection ranges intended, in the order of a few meters, the authors feel that this is not a concern. If with short transmission pulses are used the transducer's short wavelength in water allow high range resolution and minimal dead zone. The prototype transducer's detection performance in detecting flat disks and spheres has been compared to that of a flat element transducer in the range between 20 and 70cm. Results show a flatter fall off in reflection amplitude for the curved radiator than for a flat circular transducer over the same measurement range.

Two trilateration algorithms have been implemented using multiple sensors to construct an OAS. Using this approach to target detection the response time of the OAS is dependent on the number of transducers employed and the maximum detection range. Furthermore, good range and bearing resolution are possible while the configuration of the sensors that constitute the sensing array can be flexible.

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