Advanced Sonar Sensing

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Abstract

Robotics research is heavily dependent on fast, accurate, reliable and cheap sensors. Sonar sensing can fulfil these requirements in air and underwater environments. Moreover sonar physics provides robotics researchers with a natural selection capability for landmark detection in navigation problems. This paper presents new sonar results that allow high-speed accurate measurement and classification suitable for moving platforms that has been combined with interference rejection to allow multiple sonar systems to co-exist.

1 Introduction

Sonar sensing is common-place in robot applications, however *advanced* sonar sensing is not widely applied. What is meant by advanced sonar? To answer this we need to look firstly a sonar that is *not* advanced, such as the Polaroid Ranging Module (PRM) [1]. In its commonly applied form, PMR offers range to 10 metres to the first echo above a threshold[1] within a 20 degree beamwidth that changes with range and depends on target reflectivity. The user knows little about the target, the angle to the target, the strength of the echo or whether the echo comes from the same sonar system at all. *Advanced* sonar can accurately determine angle, target classification, target strength and whether that sonar system owns the echo it received – that is to allow interference rejection.

Accurate range and bearing measurements of multiple targets have been achieved in [2,3,4,5], interference rejection reported in [3,6,4], and targets classification in [2,5,7].

Knowing the shape, or class, of a target assists in robot localisation and mapping applications. It enables prediction of how the target will appear from different sensor positions, and it simplifies associating sensed environmental features to a map and building maps themselves. Mistakes in association can lead to persistent gross errors.

Properties of acoustic wave propagation and the structure of indoor environments has lead sonar researchers to the adoption of three classes of target: *plane*, 90° concave *corner* and convex *edge*. The work in [2] provides a proof that the minimum requirements to classify targets into these categories are two transmitter positions and two receivers positions. The transmitter positions need not be distinct from the receiver positions.

Sonar relies on insonifying the environment in a *cyclic* fashion, so the energy emitted in one cycle has dissipated before a new cycle is commenced[2]. In pulse-echo sonar this means a new pulse is not transmitted before there is a possibility that a previous pulse can be detected by a receiver. Similarly in CTFM (continuous time frequency modulated) sonar a new frequency sweep is not commenced until the start of the previous acoustic sweep has died out.

Existing sonar target classification methods require multiple cycles to obtain coordinates of virtual images of a transmitter in two different positions. This requires moving a single transmitter, or incorporating two transmitters into the sensor. Either way, in the interval

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[1] Discrete gain increases with time in the PRM pre-amplifier combined with integration before thresholding can complicate modelling.

[2] Some researchers are examining tagging transmissions to allow one cycle to begin before the previous has completed.

between the two cycles there can be significant air movement, which contributes to errors in the measurement, and reduces the reliability of the eventual classification.

If the interval can be reduced, reliability should be improved. Additionally, the latency before the target can be classified will be reduced.

This paper discusses new results that reduce this latency, and allow classification of a target as a *corner*, *plane*, *edge*, or unknown. The classification is compressed into a single processing cycle by firing two transmitters nearly simultaneously. Indeed, the precise separation identifies the sensor, thus providing interference rejection using *double pulse coding* – a technique presented for interference rejection alone in [3]. This paper shows that there is a natural synergy between classification and interference rejection. Moreover the signal processing can be performed at cycle rates (eg 30 Hz) by a DSP implementation, allowing on-the-fly sonar classification and interference rejection.

Advanced sonar is now more mature and should become a commercial reality, resulting in wider applications in research papers on robotics. However, single sensor modalities are rarely the answer to robotics problems and this paper highlights some unique characteristics that sonar offers compared to other range sensors such as laser techniques, stereo vision and tactile sensing.

This paper is organised as follows: Section 2 discusses how a DSP sonar sensor can be implemented to achieve an advanced sonar design. Techniques for extracting accurate range and bearing measurements are described in section 3, while section 4 illustrates how sonar can naturally extract sparse landmarks – a useful property of sonar when combined with other sensors, such as vision and laser systems. Section 5 discusses the important problem of sonar discrimination between targets that are closely spaced. Section 6 addresses the problem of interference rejection and presents results of experimental verification of difference approaches. On-the-fly classification approaches are outlined in section 7. Extensions of the author's air sonar to underwater are given in section 8. Conclusions are then presented.

2 Sensor Design

In this section, the design of a DSP based sonar sensor is discussed. The sonar sensor is built from commercially available 7000 series Polaroid transducers [8] with their front grille removed – this significantly reduces pulse lengths since the grille causes reverberation within the transducer. The sensor includes custom designed digital and analogue electronics using readily available integrated circuits, and a digital signal processor (DSP). The signal processing is implemented within the sensor which communicates the results to a host computer via high speed serial communication. The sensor measures 150 by 100 by 70 mm and is powered by a singe 5 Volt supply. Results on range and bearing accuracy, once the speed of sound is calibrated, are reported in [2] and vary with air conditions. Typical office conditions give range error standards deviations of 0.2 mm and bearing error standard deviations of 0.1 degrees at 3 metres range. The sensor is capable of detecting walls to 8 metres, but echo sampling is stopped at 5 metres to increase speed.

2.1 Transducer Arrangement

The transducers are arranged in a square shown in Figure 1, where adjacent transducers are just 40 mm apart. An important feature of sonar is that time of flight errors are well correlated in time and space [2,3]. By placing two receivers close together, very accurate measurement of bearing can be achieved despite the short baseline [2], because the bearing calculation depends critically on the difference between the two times-of-flight from a single transmitter to the two receivers. The error in this difference is typically much smaller than the straight time of flight errors since these are highly correlated.

Additionally placing the two transmitters close together produces highly correlated errors for all the four time-of-flight measurements of a target – that is T1 to R1, R2 and T2 to R1, R2. This is important because the dominant factor in determining the class of a target is the difference between the two measured bearings [9]. Classification of targets with closely spaced transmitters has been achieved out to 5 metres [9].

In summary the receiver and transmitter close spacing exploits the spatial correlation of errors in time of flights to achieve accurate bearing estimation and reliable classification.

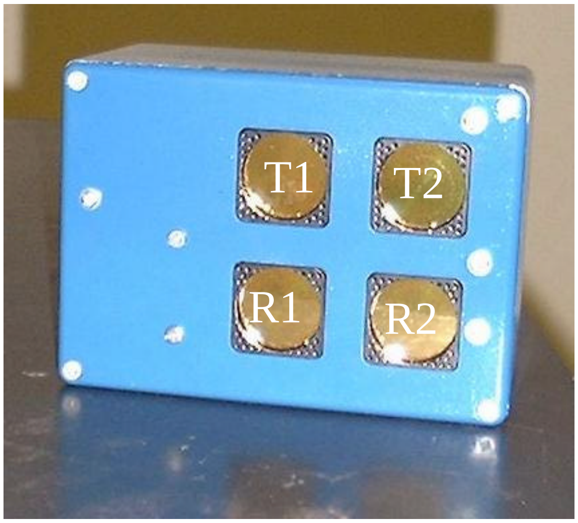

Figure 1 - The DSP sonar sensor showing transmitters T1 and T2 and receivers R1 and R2.

2.2 Electronics and Processing Hardware

Referring to Figure 2, the received signals are amplified, low pass filtered and digitised at 1 MHz and 12 bit precision, then processed on an Analog Devices 33 MHz ADSP2181. The DSP also generates the transmit waveforms and communicates with the host via an external UART.

A pulse is fired from the right transmitter first, and rapidly followed from the left (200 μs delay is typical). Echoes are digitised and processed on a DSP, yielding up to four arrival times for reflections from each target.

2.3 Interface

The sensor communicates with a host computer via a set of commands. These commands enable access to all levels of signal data from the sonar sensor, from the received pulse data samples up to the target range, bearing and class. Low level access is implemented by the DSP, sending to the host, sonar data structure addresses within the DSP memory space, so the host can interrogate intermediate results. In normal operation, packets of target information are send periodically with the sensor firing continuously.

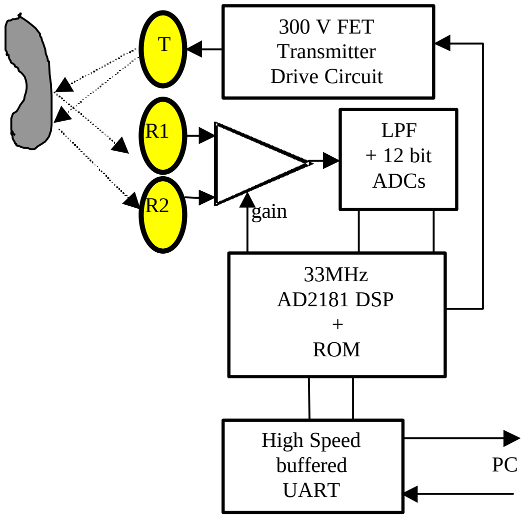

Figure 2 - DSP sonar hardware block diagram.

2.4 Time stamping and synchronisation

In real time sensing applications sensor measurements themselves are of little value without knowing the time they were collected. This is for two reasons – the sensor or platform may be moving so that sensor data needs to be fused with other navigation sensors, and the targets being sensed can be dynamic. Facilities on the sonar sensor are to be provided for synchronising the sonar local time with a host time and providing a time stamp with every measurement set.

3 Range and Bearing Measurements

The aim of the sonar data processing is to extract the arrival times of the echo pulses. From the arrival times, range and bearing to objects can be estimated by using the speed of sound and receiver geometry. Arrival times are estimated using a technique known as matched filtering first used in RADAR systems. Matched filtering obtains the arrival time by cross correlating the received echo with an echo template stored in the sensor. A template is a noise free pulse shape computed offline. The template shape depends on the angle of arrival to the transducer as shown in Figure 3. This dependency on angle can be accurately modelled by using convolution with the impulse response of a circular transducer [2]. The template is shifted across the echo to find the maximum correlation. By fitting a parabola to the maximum three correlations and their shift times, a very accurate arrival time estimate is obtained [2].

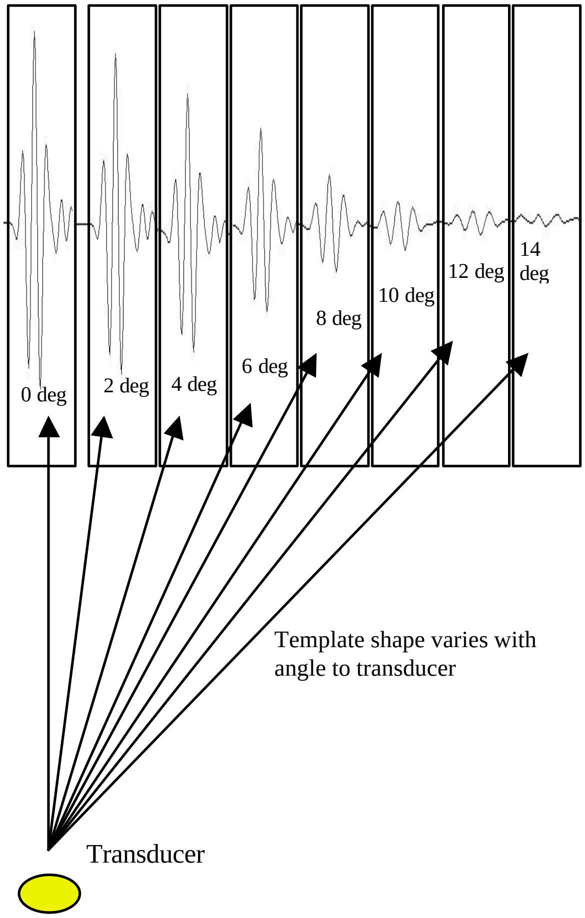

Figure 3 – Template pulse shapes as a function of angle.

The software to process the sonar echoes has been optimised for speed. Careful design of the sonar front end electronics has led to the high signal to noise ratio and consequently the data processing is significantly simplified. In particular, matched filtering is performed only on sections of the echo signal deemed to be "pulses" by virtue of exceeding a threshold. The threshold is set to 7 noise standard deviations to avoid spurious triggering. Other sonar systems reported in the literature [5,4] perform expensive matched filtering on the entire received waveform since pulses cannot be separated reliably from noise as can be done in this system. A pulse commences 30 samples before exceeding the noise threshold and ends 30 samples after falling below the threshold. A further process of "pulse splitting" is applied to separate nearly overlapping pulses by searching for a local maximum within a 60 sample sliding window.

The DSP software is organised into two stages. During the first stage, highly optimised assembly code performs on-the-fly processing of the samples from the two receivers to extract discrete pulses that exceed the noise floor. The second stage processes the extracted pulses with C code to partition closely spaced yet separable pulses and to extract arrival times using matched filtering. The processing steps are shown on an example echo signal in Figure 4.

Stage one has a main program and a timer interrupt routine that runs every microsecond. The timer interrupt routine fetches the next 12 bit ADC samples from the two receiver channels and places them into a circular buffer. The interrupt routine is also responsible for generating the transmit pulse and receiver gain changes.

The main program runs in a loop where each iteration processes the block of data acquired since the previous iteration. The two channels are processed independently through four stages: DC bias removal, thresholding, aggregation and storing into a pulse data structure

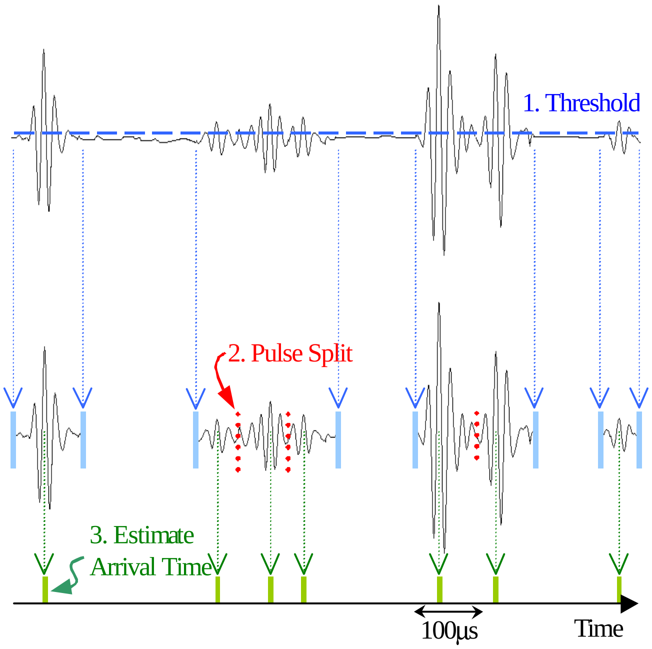

Figure 4 – DSP processing steps to extract arrival times.

3.1 Association

In order to derive the bearing angle to physical targets, pulse arrival times must be associated between the left and right receiver channels. Ambiguities are possible in this process when there are many closely spaced pulses. To guard against this, a conservative approach is adopted and possible ambiguities actively sought out and discarded. The effect of an incorrect association between two pulses is that the bearing angle is grossly in error.

Every pulse extracted from the left channel is compared with every pulse from the right. An association is declared reliable if the following conditions are met:

- Arrival times are consistent with the receiver physical spacing, SEP (=40 mm) – that is arrival times differ by less than sin(max_angle)*SEP/speed_sound
- Pulse amplitude ratio is between 0.5 and 2.0.
- Both correlation coefficients over 95%

If only the last condition is not met, the association is flagged as unreliable. Range and bearing of all associations are calculated [2] and called targets. If any pulse is associated with more than one pulse on the other receiver, all associations involving these pulses are demoted to unreliable. Pulses that are not associated with any pulse are retained and are assumed to correspond to targets in the pointing direction of the receiver and are marked extremely unreliable[3]. These targets combined with amplitude information across several measurements taken at different directions can give some indication of the roughness and position of a surface [10].

4 Natural Selection of Landmarks

In Figure 5, the sonar sensor is mounted on a mobile robot with panning mechanism and sent down a corridor. Whilst moving, the sonar performs “windscreen wiper” scans of the environment. Using odometry position information, sonar range/bearings and pan angles, targets are plotted in Figure 5. The radius of the circle representing a target is proportional the echo amplitude measured by the sonar and indicates a measure of reliability of the target. There are several important characteristics of the resulting map:

- Sparse distribution of features – low density ranging reduces map complexity for navigation.
- Only useful natural landmarks appear, such as the orientation and position of walls, positions of corners, edges or doorways.
- Reliable targets can be identified by their sonar amplitude and pulse shape integrity.

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[3] Essentially the same information that the Polaroid Ranging Module provides except amplitude is known.

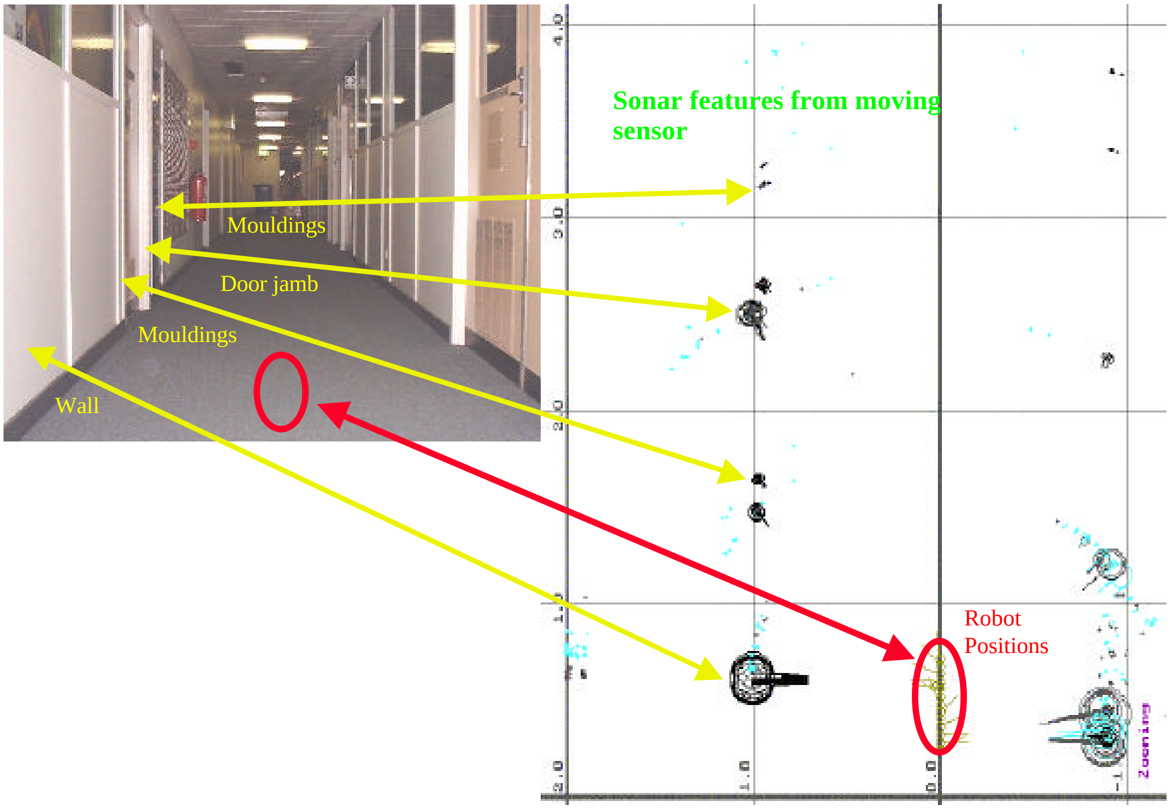

Figure 5 – Examples of natural landmark extraction with advanced sonar.

5 Discrimination

The ability of a sonar system to separate targets closely spaced in range is important. Good discrimination allows targets, for example, with quite difference bearings but similar ranges to be distinctly sensed.

Fine discrimination can be achieved using short pulses or pulse coding techniques that allow extraction of overlapping pulses. The former approach is adopted with the DSP sonar described here since it allows faster processing times. Also, to the author's knowledge, the current system achieves results unsurpassed in the literature.

Short pulses are achieved by exciting the transducer with a high energy pulse and a shorter out of phase pulse to dampen ringing effects.

An example of the smallest possible discrimination achievable by the sonar system is shown in Figure 6.

6 Interference Rejection

In order to reject interference, one needs to be able to identify your own echoes. Some form of encoding of the transmitted pulse can be deployed to this end. In this work the simplest compatible approach is taken and this is to transmit two identical pulses and use the time separation as the encoding information. Received pulses are examined and checked for this same time separation, subject to Doppler variations due to robot or target motion [3]. Other more sophisticated coding techniques exist but result in longer pulses or additional processing overhead.

Two approaches have been used to validate that pulse pairs are properly separated and the same shape:

1. [3] validates echoes by checking that the maximum difference between pulse waveforms, taken sample by sample, must fall below a threshold to be validated. Doppler-like effects slightly change the separation of returns from a moving target, and since the robot itself moves, many

returns exhibit this effect. To allow for this variation, the two returns may be shifted slightly relative to each other and tested again.

2. [9,11] uses a similar algorithm. The chief difference is the use of correlation rather than difference, and the result is rather like using the first return to define a matched filter that will identify the second.

A spin-off from the second approach is that the Doppler shift contains relative velocity information about the target and robot that may be useful.

The double pulse coding approach has been tested using experiments that introduce deliberate interference. Figure 7 shows a robot with two sonar systems that fire simultaneously – the lower one is the interfering source and the upper one is used to construct a map of the wall.

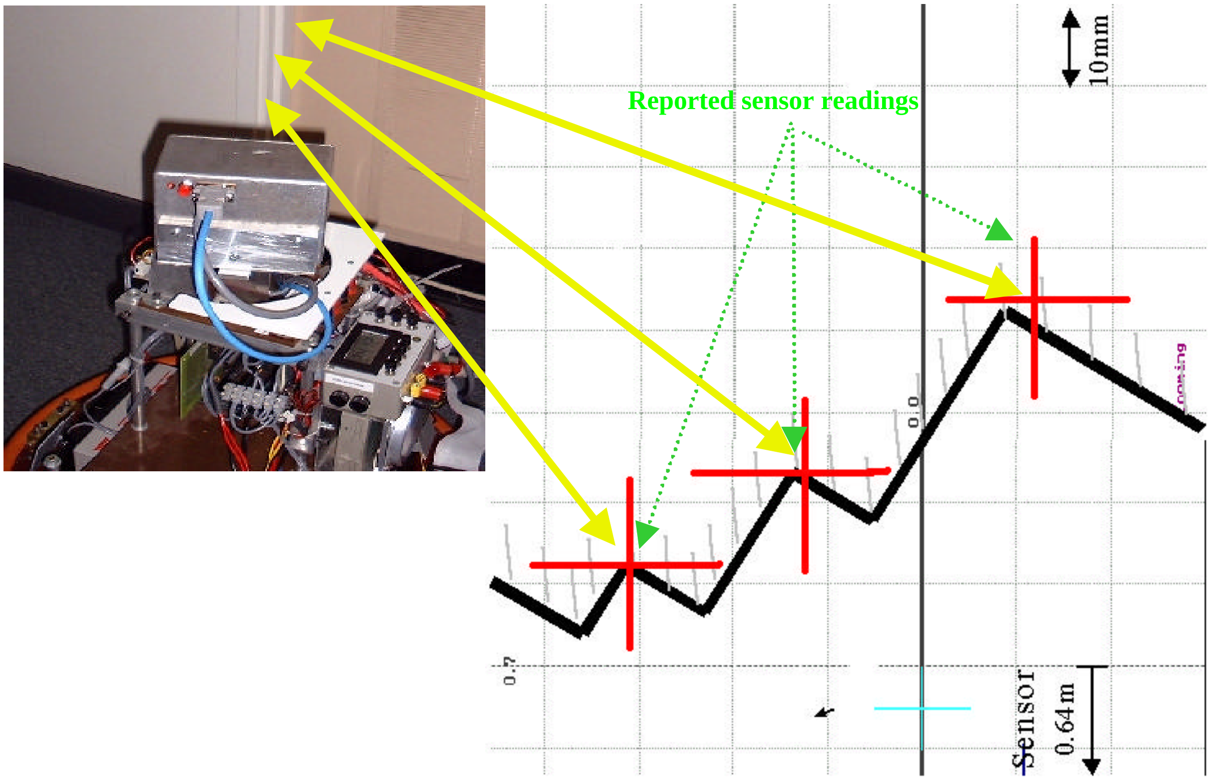

Figure 6 – Example showing the limit of discrimination with 10 mm separated targets.

Figure 8 shows results from double pulse coded interference with a difference spacing to the double pulse coding used in the map building sensor. Note that the wall floor corner is seen as a phantom target beyond the expected wall position and double reflections also add other phantom targets. Note the lack of spurious readings in the map. Compare Figure 8 with Figure 9 where the same spacing is used by the interference and the mapping sonar. The interference is clearly present in the results. Figure 10 shows the results when the double pulse spacing is varied from cycle to cycle randomly for both sensors. Most interference is rejected, but not all. The remaining interference is due to coinciding random spacings and also environmental faking effects where a single transmitted interference pulse generates two echoes with a spacing coinciding with the random spacing. Since the interference is not synchronised to the mapping sensor, these occurrences do not repeat at the same position cycle to cycle.

The advantage of randomly spaced double pulse coding is that no *a priori* code negotiating needs to be established between sensors. This allows multiple sensors to operate in the same environment without any communication required between them.

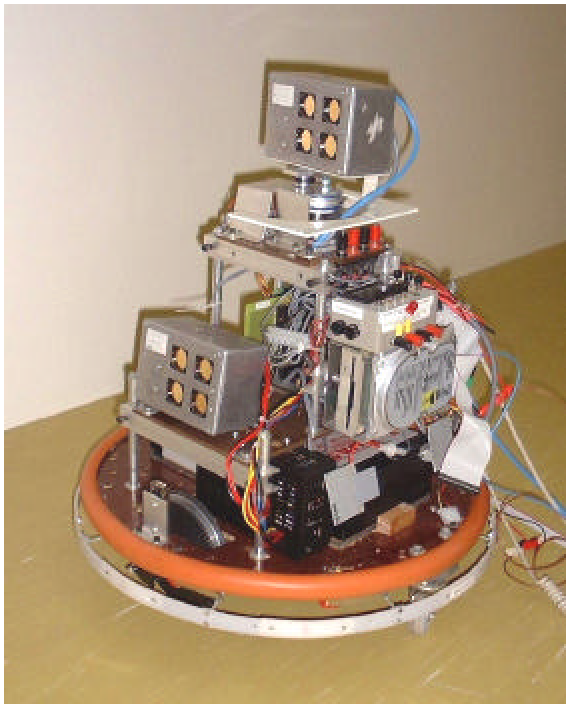

Figure 7 – Interference experiments on a robot with two sensor firing at the same wall simultaneously.

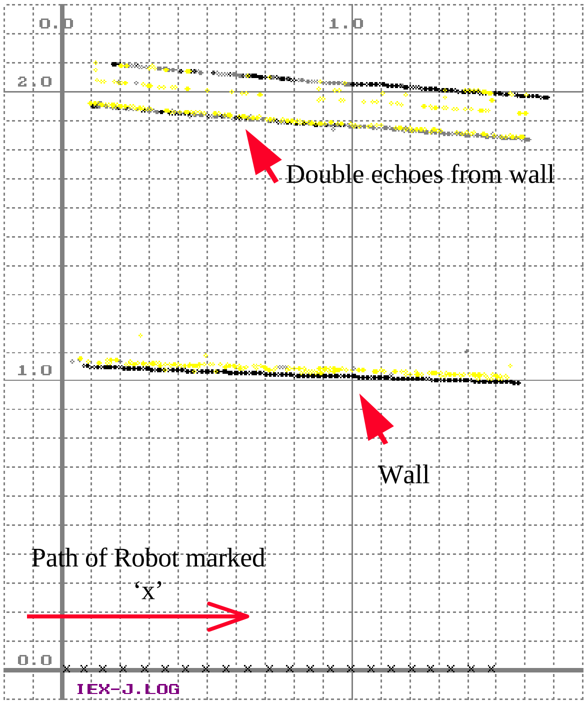

Figure 8 – Interference from a double pulse source is rejected from another sonar using a different double pulse spacing.

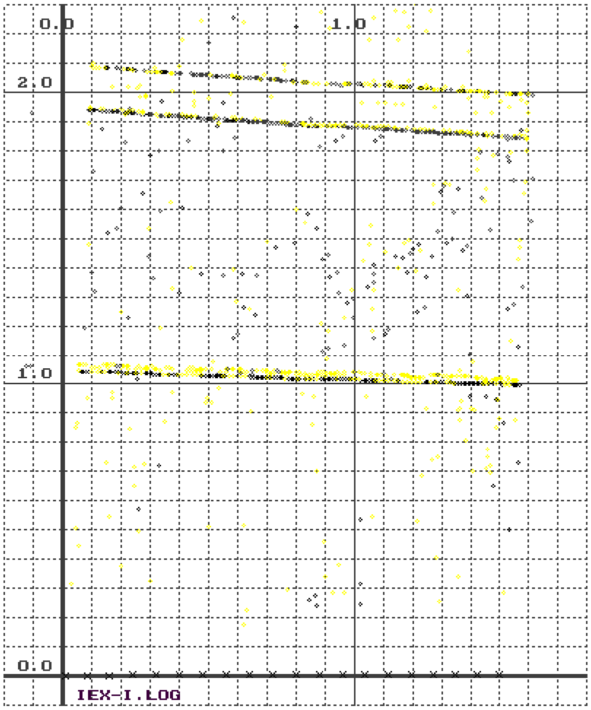

Figure 9 – Interference is not rejected since both sensors use the same double pulse spacings.

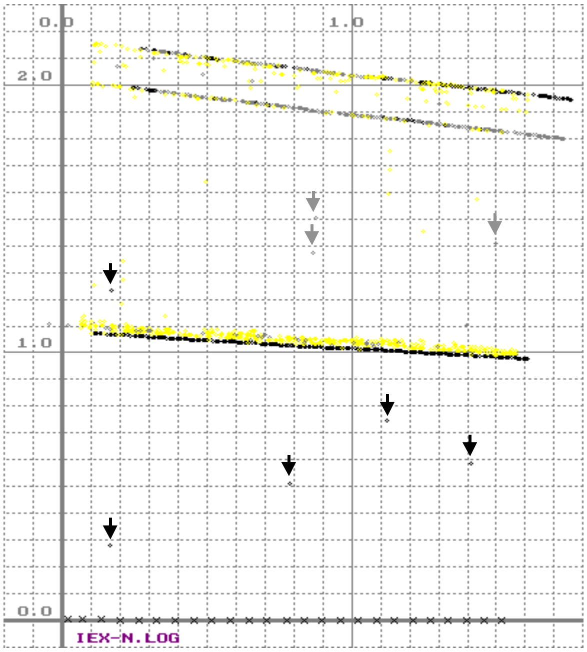

Figure 10 – Random double pulse spacing interfering with random double pulse spacing – most but not all interference is rejected.

7 Classification

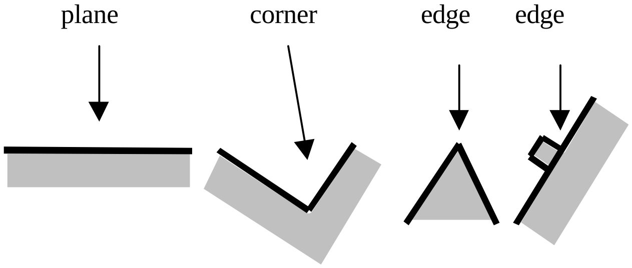

Figure 11 – Target types that sonar can classify.

Target classification into planes, corners and edges, as shown in Figure 11 has been performed in [2] in two sensor cycles by alternatively firing one transmitter and then the other. The basis for the classification can be explained simply by an analogy with virtual images in mirrors. If one looks into a plane mirror and then your left eye appears on the left. Similarly in a sonar system the left transmitter (T2 in Figure 1) will be observed to the left (in the bearing measurement) of the right transmitter T1 observed angle. However the situation is reversed when looking into a right-angled mirror – that is the left eye is observed on the right. If one looks at a polished metal chair leg (high curvature specular surface), your left and right eye images are compressed to appear to be in the same position approximately – that is the angle between left and right eyes is zero. Sonar classification can exploit the difference in bearing angles to the two transmitters to classify: positive difference = plane, negative = corner and zero difference = edge. More sophisticated approaches have been published that exploit range information as well [2,9] using maximum likelihood estimation.

Recently, double pulse coding has been combined with classification to produce a classifying measurement in *one* sensing cycle [9]. Transmitter T2 is fired a known short time (eg 200 υsec) after T1 and echo arrival times are assembled from the two receivers. Given vertical planes, corners and edges, as commonly found in indoor environments, the distance of flight T1 to R2 is the same as T2 to R1. This property is exploited to determine the double pulse coding and hence transmitter identities (ie T1 or T2) of the received pulses. Therefore classification can be performed in one measurement cycle. Measurement and classification of targets has been implemented at 27 Hz using the DSP sonar system in Figure 1 [9].

8 Some Underwater Results

Current work has been to implement the DSP sonar in an underwater environment for autonomous underwater navigation. A 200 kHz centre frequency system is under development with custom wide bandwidth transducers supplied by SensorTech in Canada. Three receiver boards based on a DSP processor and 2 MHz sampling ADCs have been completed. The echo shape is similar to the air based system and is shown in Figure 12 as captured by the DSP system and the derived spectrum shown in Figure 13. The initial aim is to achieve highly accurate range and bearing measurements to specular targets where simple geometric models exist. These targets will initially be man-made reflectors, such as existing channel markers, that act as landmarks.

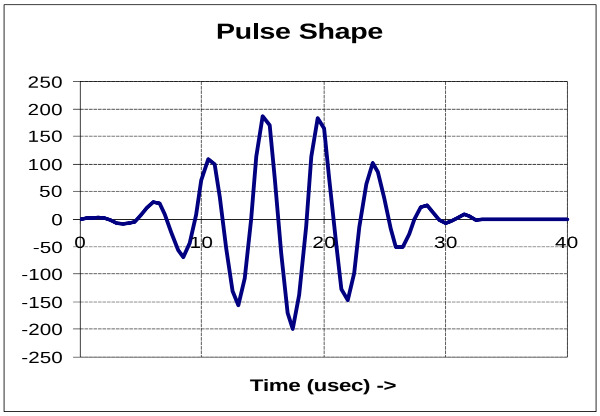

Figure 12 – Underwater echo pulse shape for maximum amplitude and minimum pulse length.

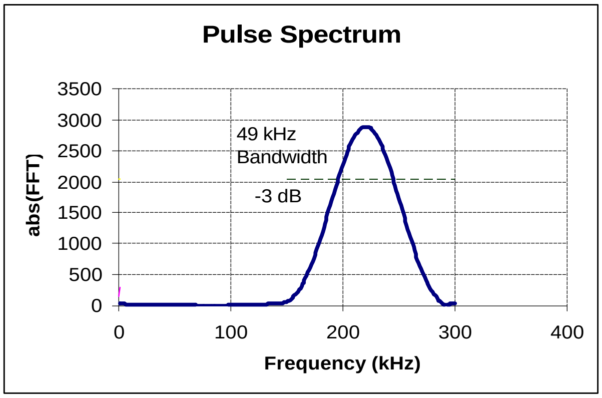

Figure 13 – Spectrum of pulse from figure 12.

9 Conclusions

This paper has presented results illustrating the capability of advanced sonar. Significant improvements in sonar research have been made in terms of range and bearing accuracy, speed, discrimination, interference rejection and classification. Recent work has been highlighted that combines interference rejection with classification in one sensor cycle, allowing robust on-the-fly applications involving classification. Future work needs to concentrate on the fusion of advanced sonar with other sensor modalities in way that exploits characteristics of each.

Acknowledgments

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References

[1] Polaroid Corporation 1982. Ultrasonic Range Finders.

[2] L. Kleeman and R. Kuc, "Mobile robot sonar for target localization and classification", International Journal of Robotics Research, Vol 14, No 4, August 1995, pp 295-318.

[3]L. Kleeman, “Fast and accurate sonar trackers using double pulse coding”, IEEE/RSJ Intern Conf on Intelligent Robots & Systems, Kyongju, Korea, 1999, pp 1185-1190.

[4] K. Jorg and M. Berg, “Mobile robot sonar sensing with pseudo-random codes”, Proceedings IEEE Conf. on Robotics & Automation, Belgium, 1998, pp 2807-2812.

[5] H. Peremans, K. Audenaert, and J. M. V. Campenhout, “A high-resolution sensor based on tri-aural perception,” IEEE Trans on Robotics and Automation, Vol 9, pp 36-48, 1993.

[6] J Borenstein and Y Koren, “Error eliminating rapid ultrasonic firing for mobile robot obstacle avoidance”, IEEE Trans. Robotics & Automation, Vol 11, No 1, pp 132-138, 1995.

[7] K S Chong and L. Kleeman, ”Feature-based mapping in real, large scale environments using an ultrasonic array”, Intern Journal Robotics Research, Vol 18, No 1, pp 3-19. 1999

[8] Polaroid Corp. *Data Sheet for Series 7000 Transducer*, Ultrasonic Components Group, 119 Windsor St., Cambridge, MA, 1987.

[9] A. Heale and L. Kleeman, “Fast target classification using sonar” accepted to IEEE/RSJ Intern. Conf on Intelligent Robots and Systems, Hawaii, USA Oct 2001.

[10] Bozma, O. and Kuc, R. 1991. "Characterizing pulses reflected from rough surfaces using ultrasound", Journal Acoust Soc of America, Vol 89, No 6, pp 2519-2531.

[11] A. Heale and L. Kleeman, “A sonar sensor with random double pulse coding”, Australian Conf on Robotics & Automation, Melbourne, 2000, pp 81-86.