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A Real Time Advanced Sonar Ring with Simultaneous Firing

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Abstract— **Sonar rings are widely used for indoor mobile robots. However, it is difficult to perform on-the-fly applications such as map building and localization using a conventional sonar ring due to low speed, accuracy and interference. Digital Signal Processing (DSP) techniques and interference rejection ideas are applied in this paper to design a new more sophisticated, fast and accurate sonar ring called an advanced sonar ring. The advanced sonar ring consists of 48 ultrasonic transducers 24 acting as transceivers and 24 acting as receivers, seven DSP echo processor boards, twelve four-channel 12-bit 500 kHz ADCs and low noise variable gain preamplifiers. The sonar ring is able to cover 360 degrees around robot with simultaneously firing of all 24 transmitters. Transmission and echo analysis are performed at repetition rates of about 15 Hz, depending on the environment, for ranges up to six metres. Accurate distance and bearing measurements of objects are performed in the DSP system using matched filtering techniques. The paper presents new transmit coding based on pulse duration to differentiate neighbouring transmitters in the ring. Experimental data show the effectiveness of the proposed system.**

Keywords - ultrasonic sensor; sonar ring; simultaneous firing; multiple DSP sensor; real time processing; interference rejection.

I. INTRODUCTION

Sonar provides robots with a low cost active range sensor. A sonar ring is a set of sonar sensors configured around the robot to provide sensing of the surrounding environment without the mechanical complication and delays associated with scanning sensors. Conventional sonar rings deploy Polaroid ranging modules or equivalent and suffer from poor bearing accuracy and interference problems [1, 2]. Furthermore, the performance of robotic tasks such as simultaneously localization and map building, target tracking, obstacle avoidance and navigation are highly dependent on the availability of fast, accurate and on-the-fly sensing. Teruko Yata developed a sonar ring that allows simultaneous firing and thresholding of echo signals to measure reflectors with a bearing accuracy of around 1 degree [3, 4]. In contrast, Digital Signal Processor (DSP) systems have enabled the ultrasonic echo to be sampled at 12 bit amplitude resolution and 1 microsecond sample time and then processed in near real time to measure range to 0.2 mm and bearing to 0.1 degrees [5]. This approach is fast and accurate but operates in just one direction within the beamwidth of the transducers. Mechanical scanning and many measurements taken in sequence are needed to cover a full 360 degrees. With the decreasing cost and increasing performance of DSPs, it is now possible to perform intensive sonar echo processing around an entire ring of transducers from a single simultaneous set of transmissions in near real time. Thus the sequential scanning of the individual sonar sensors has been condensed into one measurement cycle of the advanced sonar ring. The use of DSP local processing relieves communication problems with a host computer as in [6] where all echo samples are sent through the computer bus. A second advantage is that the DSP offers optimised instructions for high-speed signal processing over a general purpose computer – in particular the matched filter operations are extremely fast. Thirdly, there is little signal degradation since the physical distance between receiver and pre-amplifiers is reduced, allowing much better shielding to the front end of the receiver electronics.

This paper presents the first self-contained sonar ring that achieves accurate distance and range measurements around robot at near real time rates – termed an advanced sonar ring. The repetition rate of the sonar ring is limited by the time of flight to the furthest range of about 6 metres combined in parallel with DSP computation and serial communication between DSPs and a host computer. We achieve a repetition of approximately 15 Hz in this paper.

The basic idea is to calculate time-of-flight for each receiver by means of signal processing technique similar to that used in RADAR [7]. This technique is matched filtering (also called template matching) which is the minimum variance arrival time estimator in the presence of additive white Gaussian noise on the echo. A matched filter is based on finding the peak of the cross correlation of the echo with an *a priori* calculated template. This technique has been extensively used in [5, 6, 8, 9]. This paper presents a DSP sonar ring consisting of 48 transducers in 24 pairs each pair has a transceiver and a receiver so the ring has 24 transmitters firing simultaneously and 48 receivers. The simultaneous firing of a sonar ring has recently been used by other researchers for obstacle detection [10, 11]. In the advanced sonar ring, the bearing calculation is based on the difference between arrival time of echo in two receivers and a triangulation technique. As each pair approximately

15 degrees, the sonar ring gets information from almost all of the full 360 degrees around robot. Each group of eight transducers is controlled by a local slave DSP that communicates with a single master DSP that in turn relays results of all slaves to a host computer over a serial line. One of the advantages of this configuration is that it relieves the computational burden of the host computer allowing computationally intensive applications to take place on a moving platform.

In the next section, we briefly introduce the hardware modular decomposition of the sonar ring. Section 3 discusses the implementation of on-the-fly processing using highly optimised assembly code. This section also explains the implementation of matched filtering within a DSP context, yielding very accurate range and bearing estimation. Experimental results are presented in section 4 to show the effectiveness of the proposed system. Conclusions and a discussion of further work form the last section of the paper.

II. MULTI DSP HARDWARE ARCHITECTURE

The custom designed multi DSP sonar ring sensor is shown in Fig. 1 mounted on an ActivMedia Pioneer 3 DX mobile robot. The various components of the advanced sonar ring are described below.

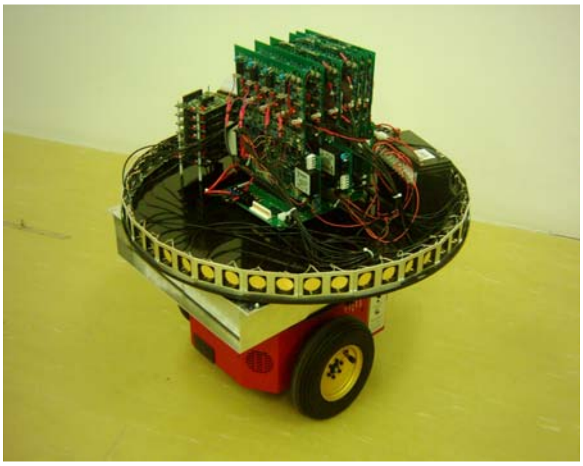

Figure 1. Advanced sonar ring mounted on an ActivMedia Pioneer 3 DX mobile robot.

A. A ring consisting of 48 transducers

A group of eight Polaroid 7000 series transducers, arranged in four pairs, is controlled by a digital slave DSP board and an associated analogue board. The ring contains 24 pairs with each pair containing a transceiver and a receiver 40.5 mm and 15 degrees apart. The sensor is capable of covering full 360 degrees around robot when the effective beamwidth of each pair of transducers is at least 15 degrees and this occurs for highly reflective specular targets at ranges closer than 2.8 m. Fig. 2 shows the viewing area for a pair of transducers observing a plane target at positions out to 4 m range.

B. Six analogue slave PCBs

Each slave board is responsible for controlling the transmission and data acquisition process for four pairs of transceiver and receivers, grouped into four pairs. Also the board contains a high voltage DC-DC converter to produce a 300 V bias on the 8 transducers.

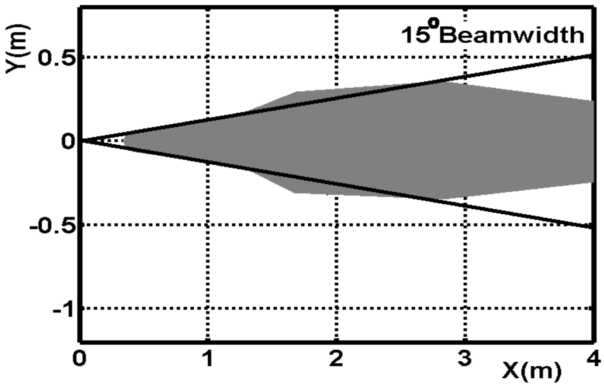

Figure 2. The measured beamwidth of a pair of transducers in gray – the solid line indicates the requirement for the ring to cover 360 degrees.

C. Six digital slave PCBs

Each of the six digital slave boards contains a DSP and two Analogue to Digital Converters (ADC) and connects to an analogue slave board via a ribbon cable. The DSP is responsible for generating the transmit pulses for the four transceivers and processing the echoes collected by the eight transducers. Two 12-bit ADS7862 ADCs are configured to allow pairwise synchronised sampling of 8 input channels at 250 kHz sample rate. An Analog Devices 2189M DSP was chosen due to the single clock cycle access to on-chip RAM of 192 k bytes, allowing echoes to be extracted, stored and processed within the DSP chip.

D. A master PCB

A master board contains a 2189M DSP, flash memory and a high speed buffered UART. It communicates with a central computer via the high speed serial link and with all the digital slave boards via a PC104 type connector using the Internal Direct Memory Access (IDMA) feature of the 2189M DSPs.

Fig. 3 shows the block diagram of the hardware architecture. The receiver channels are amplified and low pass filtered before sampling with ADCs at 250 kHz. The transmitter circuitry allows a programmable digital pulse train to be sent to the transducer without the need for preloaded memory buffers as required previously [6]. Instead the slave DSP directly controls the transmit logic every microsecond under interrupt control. Varying gain preamplifiers increase the gain in a fixed profile after each firing. The master board sends all commands and reads the high level data from slave boards via a PC104 type connector, using IDMA of the DSP which allows high speed access to on-chip memory of the slave DSPs. The master DSP relays results from all slave to a host computer using a RS232 serial port.

In the first design, the advanced sonar ring contained both analogue slave and digital slave on the same PCB but due to the high speed of the IDMA between slave processors and master processor communication errors were encountered. The digital part was re-designed on a four layer board and the analogue slave was separated. In addition, we have encountered problems protecting the ADCs from being destroyed through power supply transients and electrostatic discharge during construction.

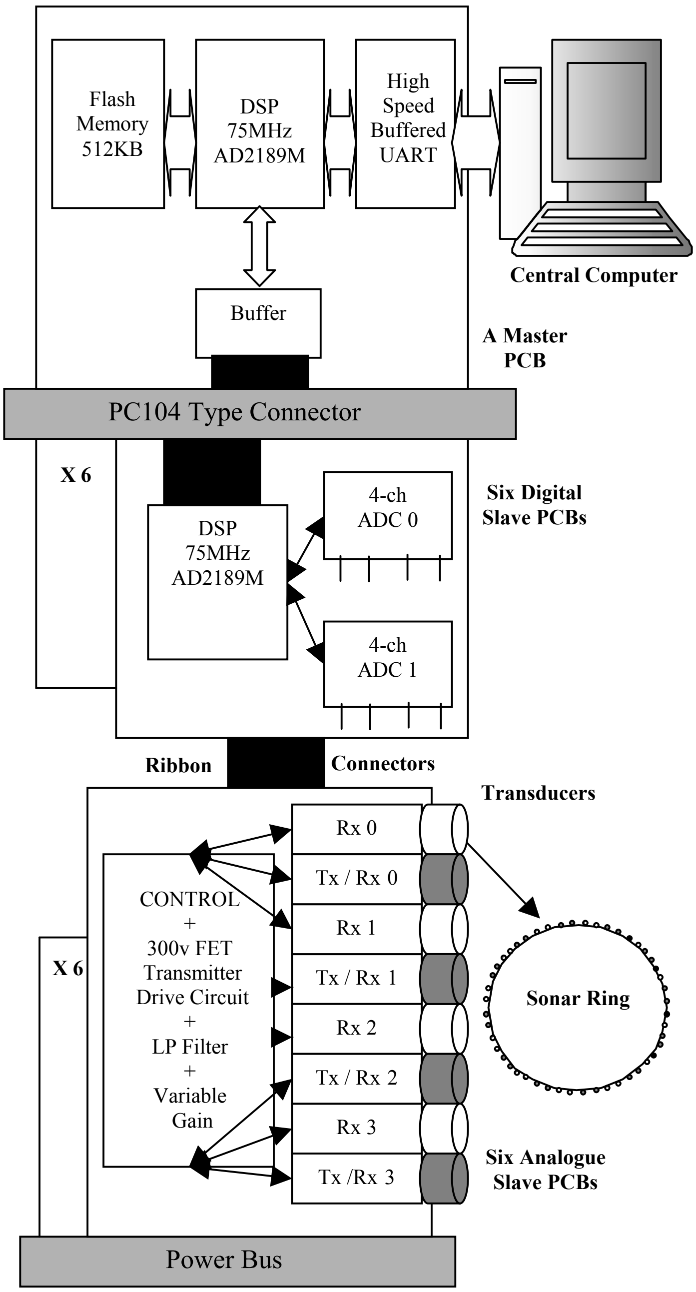

Figure 3. Advanced sonar ring hardware block diagram

III. REAL TIME ECHO PROCESSOR

The DSP software is stored in the flash memory and contains both master and slave programs. After turning on the sensor, the master is booted via the byte DMA method of ADSP-2189M. This software is a command parser capable of communication with the host computer and all digital slave boards, allowing the central computer to control all parts of the advanced sonar ring. By sending a command to the master, it can boot all digital slave boards using internal DMA mode of ADSP-2189M. The IDMA provides 16-bit high speed access to on-chip memory of the slave, even during slave processing. While the slave boards fire the transmitters and calculate the results, the master board reads the high level data using IDMA from each slave and relays the data to the host computer. A fire command is issued to all slaves simultaneously, thus synchronizing the firing of all transceivers to within on clock cycle or 13 nanoseconds. The software of each slave can communicate with the master by a command parser containing some commands to access low level data. The most important part of this software is an echo processor that is organised into two phases. During the first stage, assembly code performs on-the-fly processing of the samples from the eight receivers to extract discrete pulses that exceed the noise floor. On-the-fly processing is essential not only to have a real time sensor but also to conserve the on-chip data memory of the DSP. The second stage processes the extracted pulses with C code to extract arrival times using matched filtering.

A. DSP Phase One Processing - Pulse Capturing

The phase 1 consists of highly optimised assembly code to extract pulses from eight receiver channels and save them into pulse buffers. This real time program enables approximately 128k words of raw receiver data to be processed in a transmit cycle to yield pulse results within the 48k words of data memory. The software is run while receiving echoes and processes all eight channels within 150 instruction cycles or two microseconds. This phase has a main program and a timer interrupt routine that runs every two microseconds. Each slave board contains two 4-channel ADCs producing multiplexed 2+2 data. The timer interrupt routine fetches the next 12 bit ADCs samples from the eight receiver channels and places them into eight circular buffers. Therefore the sampling rate for each receiver channel is 250 kHz. The interrupt routine is also responsible for generating the transmit pulse.

The main program runs in a loop where each iteration processes the block of data acquired since the previous iteration. The phase 1 processing occurs concurrently with respect to the capture time and consequently must keep up with the incoming data to avoid buffer overflow errors. The eight channels are processed independently through four stages: DC bias removal, thresholding, aggregation and storing into a pulse buffer (Fig. 4).

- Filtering**:** An optimised high pass software filter removes the DC voltage of echo. This process operates in-place on data in each circular buffer [5].
- Thresholding**:** Each receiver sample is compared with a threshold to classify the sample as noise or

part of an echo pulse. Since an echo pulse can legitimately pass through zero, a block processing technique is used. Each block of eight samples containing at least one sample with amplitude greater than the threshold are deemed to be part of an echo. An adaptive threshold level is applied to allow for different time varying gains in the receiver preamplifiers resulting in different noise levels. The threshold level is increased when the pulse buffer is fully occupied and is decreased when it is nearly empty. Due to limitation in size of each pulse buffer especially in a cluttered environment, this adaptive method is useful.

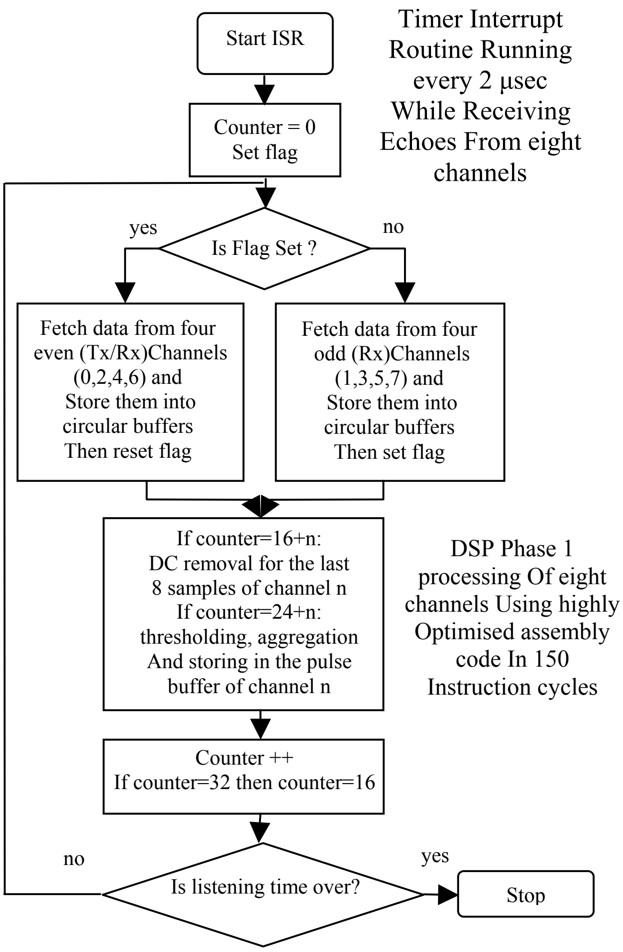

Figure 4. Phase one real time processing flow chart

- Aggregation and Storing**:** When there are two or more consecutive blocks exceeding the threshold level, the software merges them along with the resulting ranges for later template matching. Each receiver channel has its own pulse buffer. Due to the transmitted pulse shape, the length of an echo should be greater than eight samples so a block of eight samples is deemed to be a noise. This reduces the time required for matched filtering in the next stage.

B. *DSP Phase Two Processing – Matched Filtering and Bearing Estimation*

Phase two processing occurs in the DSP after all receiver channels have been logged and stored simultaneously in the pulse buffers. The processing time in this stage occurs in addition to the time of flight between transmitting and receiving the furthest echo – approximately 32 milliseconds. This processing time then directly impacts on the real time performance of the sensor since it takes place sequentially with respect to the capture time.

To determine the echo pulse arrival times, matched filtering is performed on the echo pulses extracted during phase one of the processing. Template matching obtains the arrival time by cross correlating the received echo pulse with an echo template stored in the DSP. A template is a noise free pulse shape computed offline from a calibration pulse obtained from a plane at one metre range straight ahead. The template is shifted across the echo to find the maximum correlation [5]. By finding a parabola to the maximum three correlations and their shift times, a very accurate arrival time as a fraction of the 4 microsecond sample time is estimated [8].

A complication in the template matching is that the pulse shape depends on the angle of arrival and the range. These templates for different ranges and angles can be computed offline [8]. For each metre of range several different template pulses are computed and stored within the DSP program memory corresponding to all the possible arrival angles. The DSP is capable of performing a very fast cross-correlation process. Matched filtering is tried across all possible angles at the given range and the highest match is selected to estimate an arrival time.

After all arrival times are estimated, the bearing estimation is performed for all targets seen by both receivers of each pair using a triangulation method. If a target is seen by just one of the receivers it is deemed to be an unreliable target. At the end of the calculation, the slave boards are waiting to be read by the master board and after the high level data of all slave boards are read and sent to the central computer, the master board sends another fire command simultaneously to all the slave boards.

IV. Experimental Results

A. *Target Association Results*

To illustrate the DSP processing, the sonar ring was placed among a set of reflectors. The test environment consists of concave right angled corners and planes as shown in Fig. 5. Measured targets are shown as a line connecting a pair of transducers to the observed object.

The DSP sonar ring can be commanded to continuously report parameters on up to 20 pulses per receiver. Table I and II are these parameters in one position of the ring. The amplitude column represents the maximum amplitude of the pulse. Amplitude information is useful in classifying targets based on their reflectivity and also can be exploited in the association process discussed below. The correlation coefficient lies between –1 and +1 and is an important outcome of template matching [8]. It represents how well the received pulse matches the closest shaped template. A correlation coefficient above 80% indicates that a reliable arrival time has been obtained. Due to the slower sampling rate employed here of 250 kHz, the correlation coefficient is usually less than the correlations from a 1 MHz sample rate in [5]. Values below 80% are unreliable for bearing estimation purposes but still give an indication that an obstacle is present. In the current implementation, stage 2 processing can be performed in about 35 milliseconds for all receiver channels and this translates to a maximum sensor cycle time of 32+35 milliseconds or a 15 Hz repetition rate.

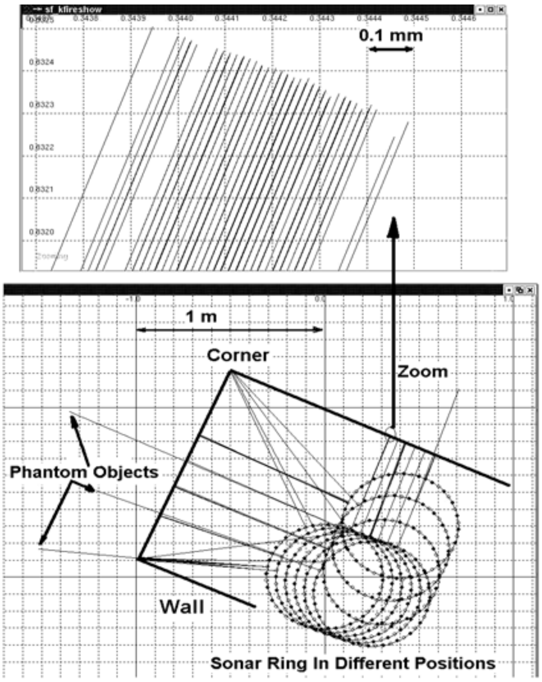

Figure 5. Targets associated by advanced sonar ring in the real environment

In order to derive the bearing angle to physical targets, pulse arrival times must be associated between the left right receiver channels in each pair of transducers. Ambiguities are possible in this process when there are many closely spaced pulses.

Every pulse extracted from the left channel is compared with every pulse from the right. An association is declared reliable if both correlation coefficients are over 80% and arrival times are consistent with the receiver physical spacing (=40.5 mm) – that is arrival times differ by less than sin(max_angle)*40.5/speed_sound.

TABLE I. RECEIVERS PULSE DATA FROM ENVIRONMENT

Transd. Pair no	**Arrival Time (μsec)**	**Range (m)**	**Amp. (ADC counts)**	**Correl. Coeff %.**
16	3482.035	0.591946	1492	87
19	5867.018	0.997393	1765	86
22	3768.959	0.640723	1514	86
23	4039.176	0.686660	1155	83

TABLE II. TRANSMITTER/RECEIVERS PULSE DATA FROM ENVIRONMENT

Transd. Pair no	**Arrival Time (μsec)**	**Range (m)**	**Amp. (ADC counts)**	**Correl. Coeff.**
16	3482.112	0.591959	657	95
19	5867.759	0.997519	1082	92
22	3768.606	0.640663	757	95
23	4030.988	0.685268	977	90

Fig. 5 shows results from different positions of the ring. The results of associating the measurements in Tables I and II are presented in Table III. The estimation of standard deviation is based on 2000 repetitions of association in one position shows a very small dispersion from the average value, presenting the repeatability of the advanced sonar system.

TABLE III. TARGET ASSOCIATION RESULTS

	Associated Targets			
	Wall 1	***Corner1***	***Wall 2***	***Corner2***
Pair No	16	19	22	23
Range to Rx (m)	0.5919	0.9974	0.6407	0.6867
Bearing to Rx (deg)	1.9377	0.9851	1.9181	3.5734
STD of Range(m) in 2000 Repetitions	9.13 E-6	1.05 E-5	5.72 E-5	2.76 E-4
STD of Bearing(deg) in 2000 Repetitions	0.0097	0.0103	0.0240	0.2861

B. Interference Rejection Concept and Results

In a simultaneously fired sonar ring, multiple transducers must share the same airspace and the pulses transmitted by one transducer may be received by others – this form of interference is also known as crosstalk [11].

When the same sonar pulses are used for all transmitters, a receiver cannot determine whether echoes originate from the same pair or from some other pairs of transducers. The matched filtering of all received pulses possibly results in many phantom objects.

In the advanced sonar ring, each slave board can generate its own pulse shape and therefore using different pulse shapes can potentially eliminate most crosstalk. In this experiment, we divided the transducers into two banks, slaves 0, 2 and 4 as bank 0 and slaves 1, 3 and 5 as bank 1. The two banks are interleaved so adjacent pairs of transducers belong to different banks. Fig. 6 shows voltage waveforms and captured echo pulse shapes of bank 0 and bank1.

An experimental comparison that shows the advantages of creating different pulse shapes for adjacent transmitters can be seen in Fig. 7. The phantom objects resulting from crosstalk between two banks are eliminated due to significantly lower correlation than genuine echoes. In this method, different templates for each bank have been saved in DSP, resulting in rejection of more than 50% of crosstalk. In addition, it is possible to have more banks i.e. more pulse shapes to achieve better interference rejection but since interference mostly occurs between adjacent pairs, most of the crosstalk is eliminated with just two banks.

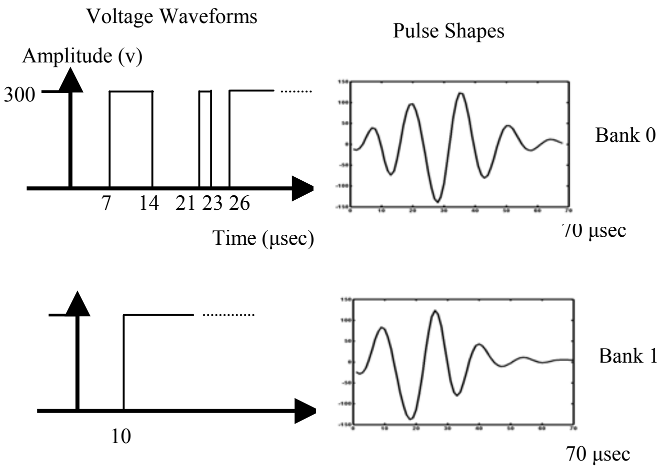

Figure 6. Voltage waveforms used to drive transmitters and echo pulse shapes of bank 0 and bank 1

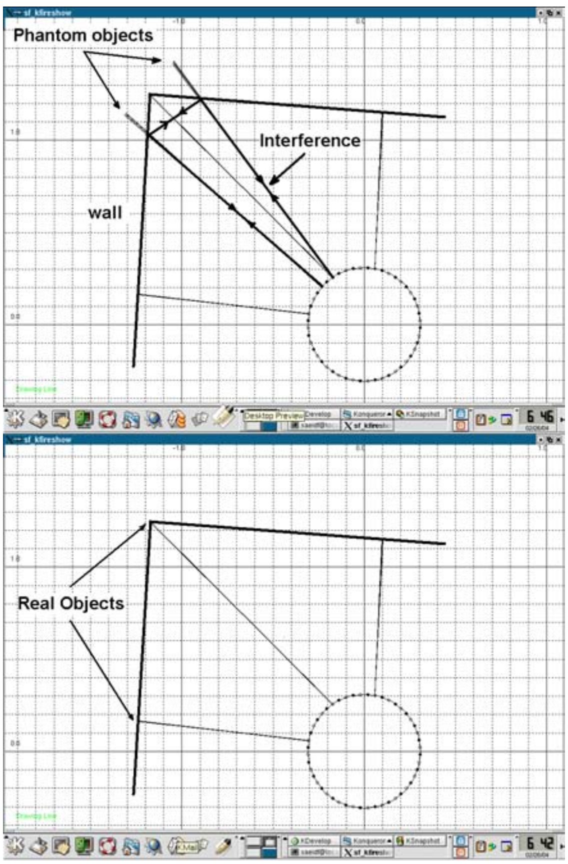

Figure 7. Target association results before and after applying interference rejection idea

V. Conclusions and Future Work

The paper has presented a new approach to a multi DSP real time sonar-ring sensor based on the real time DSP sonar echo processor [5] and the template matched arrival time estimator that has proven accuracy and robustness characteristics [8]. The performance of the sensor has been illustrated by experimental results.

The new sensor has some advantages. Firstly, processing can be done locally obviating the data communication problem to a central computer. Secondly, due to real time signal processing, central processing can be devoted to higher level applications such as simultaneously localization and mapping (SLAM). Finally, the sonar ring enables simultaneous sonar sensing of the surroundings of a robot that is useful for on-the-fly applications on moving platforms.

Future work will be performed on high level applications such as SLAM, obstacle detection and path-planning in real time.

Acknowledgment

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