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Mobile Robot Sonar Sensing with Pseudo-Random Codes

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Abstract

One of the most severe problems in conventional mobile robot sonar sensing is from the literature known as »crosstalk«. This article addresses the crosstalk-problem and presents first experimental results of a new approach which allows the simultaneous firing of sonar sensors. At the same time frequent misreadings caused by crosstalk or external ultrasound sources are eliminated. Moreover, the range resolution as well as the lateral resolution of a sonar sensor are significantly increased. This is achieved by carefully designing the emitted burst, i.e. by using appropriate pseudo-random sequences together with a matched filter technique.

1 Introduction

Conventional time-of-flight (CTOF) sonar sensing is widely used within the autonomous mobile robot research community. A burst with a fixed frequency and a width of T ms is transmitted toward a target and the resulting echo is detected (Fig. 1). The elapsed time t between initial transmission and echo detection can be converted to distance d with respect to the speed of sound c: $d = ct/2$. An echo is valid if its amplitude exceeds a certain threshold.

However, CTOF sonar sensing suffers from several severe problems: *poor angular resolution*, *limited range resolution*, *specular reflections*, and *frequent misreadings* due to either external ultrasound sources or crosstalk.

The problem of accepting misreadings is increased in mobile robot applications if a robot is equipped with multiple sonar sensors. Depending on the environmental conditions, the sensors will randomly influence each other if a fast firing strategy such as scheduled firing is applied e.g. to perform fast collision avoidance. This phenomenon is called *crosstalk* and results in range readings which are generally smaller than the real ones (i.e. false) and thus unacceptable. The problem becomes even worse if two or more sonar-based mobile robots are performing operations in the same environment.

In order to correct errors resulting from the straightforward interpretation of the range readings obtained by a CTOF sonar sensor system, many approaches try to a posteriori correct the errors by applying grid-based techniques [4], [6], [8]. In [5], Borenstein & Koren present their EERUF-algorithm for error eliminating rapid ultrasonic firing of a set of CTOF sonar sensors. This algorithm is a first attempt to a priori reject erroneous range readings caused by noise and crosstalk. EERUF introduces the method of *alternating delays* which is combined with the conventional *scheduled firing* scheme and the method of *comparison of consecutive delays*. The au-

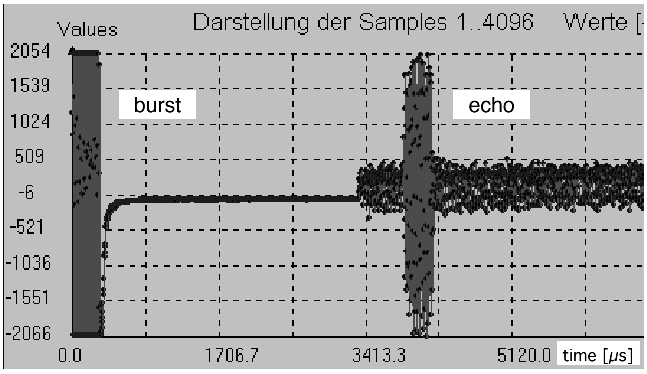


Fig. 1: Transmit/receive cycle of a CTOF sonar sensor

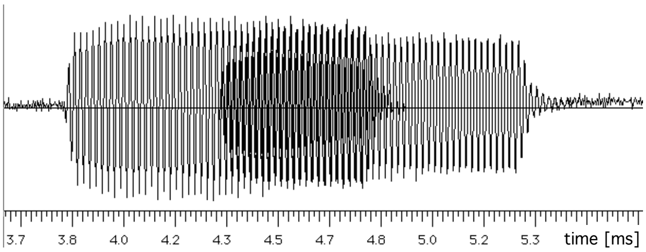
thors claim that their algorithm reduces the number of erroneous range readings by one or two orders of magnitude.

This paper addresses the crosstalk-problem and presents first experimental results of a new approach [10] which is an attempt to a priori reject erroneous range readings caused by noise and crosstalk. The approach utilizes the pulse compression technique together with a matched filter receiver which are well known from existing radar applications and allows to fire multiple sonar sensors simultaneously. Moreover, the range resolution as well as the lateral resolution of a sonar sensor are significantly increased. The approach was inspired by the work of Audenaert et.al. [1] and Sabatini & Spinelli [13].

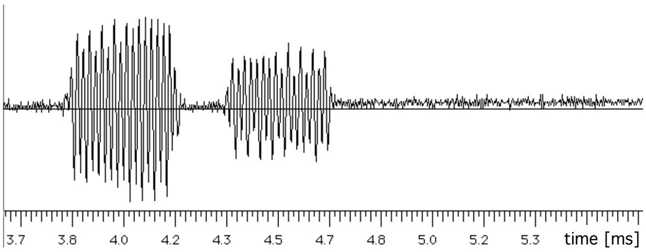
The rest of the paper is organized as follows. Section two addresses pulse compression technique and matched filter receiver since both are essential within the scope of this paper. The key idea behind our approach is introduced in section three. Since the approach requires a specific hardware, section four describes our experimental platform. Section five presents experimental results and section six offers some concluding remarks.

2 Pulse Compression & Matched-Filter Receiver

Using conventional time-of-flight sonar sensing, two or more consecutive objects cannot be distinguished if they are so closely spaced that their individual echoes overlap. This *limited range resolution* depends on the width T of the emitted burst. Fig. 2a illustrates this. It shows the overlapping echoes of two consecutive targets resulting from a conventional burst (T = 1ms). Both echoes overlap because the relative distance Δd of the targets is smaller than $cT/2$. Please note, that the strength (amplitude) of an echo depends on both, the distance and the reflecting properties of the target. Clearly, making the burst shorter in duration will reduce the ambiguity caused by overlapping echoes (Fig. 2b). Nevertheless, as long as the burst has some width there will be some minimum time delay between objects which is necessary to have unambiguous reception. To prevent interference between echoes, targets must be separated in time delay by at least the width T of the transmitted pulse, i.e. the relative distance Δd between two targets must be greater than $cT/2$. Assuming that the speed c of sound is 33cm/ms both echoes do not overlap if $\Delta d > 16.5$cm for T = 1ms ($\Delta d > 5.5$cm for T = 330μs). Thus, reducing the duration T of the burst, on the one hand improves the sensor's range resolution. On the other hand the sensor's maximum range becomes reduced resulting from the echo's lower energy level. What is needed is a transmitted burst of sufficient duration to maintain the required energy level together with a clever means of processing the returned signal so that the data can be treated as if it were from a short burst. In other words, we need to design a burst so that the returns from different time delays can be separated [9]. This can be accomplished by using a burst with a sharp autocorrelation function. The separation of multiple objects is achieved by processing the return using e.g. a matched filter receiver and applying a peak detection algorithm. The output of a matched filter receiver is a measure of how precisely the received signal and the reference match. It can be proven that the matched filter is statistically the optimum filter for performing this operation under the condition that the emitted burst has a sharp autocorrelation function [9]. With a matched filter receiver, the range properties improve as the "time-bandwidth" product of the signal increases. Thus, for any improvements, either



a) Overlapping echoes of two consecutive targets (T = 1ms, $\Delta d \approx 8$cm)



b) Non-Overlapping echoes, resulting from a shorter burst (T = 330μs, $\Delta d \approx 8$cm)

Fig. 2: Using CTOF sonar sensing consecutive targets can only be distinguished if their individual echoes do not overlap.

the duration or the bandwidth of the burst must be increased. When increasing the time-bandwidth product, however, we must retain good autocorrelation functions to avoid ambiguities. Comprehensive descriptions of a matched filter receiver may be found in [7] and [12].

3 Key idea: Applying Pseudo-Random Codes

Against the background of this discussion and the cross-talk-problem mentioned above the key idea behind our approach arose from the consideration that it should be possible to fire a set of sonar sensors in parallel provided that the individual bursts of the sensors are designed such that each sensor is able to identify its own echo within the received return. Since the sonars are fired in parallel each return will most likely be a superposition of multiple echoes.

With two sonar sensors this is possible by emitting a linear f-m signal per sensor, one sweeping up and the other sweeping down (same frequency range). Since both signals do not correlate, each sensor is able to identify its own echo(es) by autocorrelation. However, this is not possible for more than two sensors.

Following, we will show that sonar sensors can be fired in parallel by emitting random noise, i.e. the burst of each individual sonar sensor is a pseudo-random sequence. If each of these pseudo-random sequences has a sharp autocorrelation function and if two arbitrary pseudo-random sequences do not correlate, then each sonar sensor can identify its own echo by applying a matched filter technique.

Since there is no theory to specify the autocorrelation behaviour of a particular sequence in advance [2] it has to be determined experimentally whether or not stochastic signals have good autocorrelation functions. Thus, we performed a series of simulations, first [10]. One result of these simulations was that it is easily possible to find pseudo-random sequences showing the correlation behaviour mentioned above. Given a fixed frequency range, other simulations proved that the quality of the autocorrelation function improves if the duration of the burst is increased. To sum up, these results correspond with the fact mentioned above, that the range properties of a matched filter receiver improve as the time-bandwidth product of the signal increases.

In order to investigate the applicability of this approach under real world conditions i.e. using real transducers and real returns we performed a series of physical experiments. An essential prerequisite of these experiments was the prototypical implementation of a specific sonar sensor hardware which is described in the following section.

4 Experimental platform

At present our experimental platform is capable of firing two sonar transducers simultaneously at a (theoretical) maximum frequency per emitted signal of 150 kHz. Please note, that each transducer is alternately operated as transmitter or as receiver. The hardware supports both, the transmission of arbitrary signals (fixed frequencies, frequency sweeps, pseudo-random sequences) and the sampling & processing of the returns. Central element is a commercially available DSP-board [14] which is based on the digital signal processor TMS320C44.

During the transmit phase the DSP acts as a function generator. The digital signal provided by the DSP is converted into an analog equivalent which is then fed into a high-voltage amplifier. This device is centered around a high-voltage OP-amp (Apex PA85) and became necessary since we use electrostatic transducers (Polaroid® 8000 series) which demand a voltage bias of 150 VDC and a

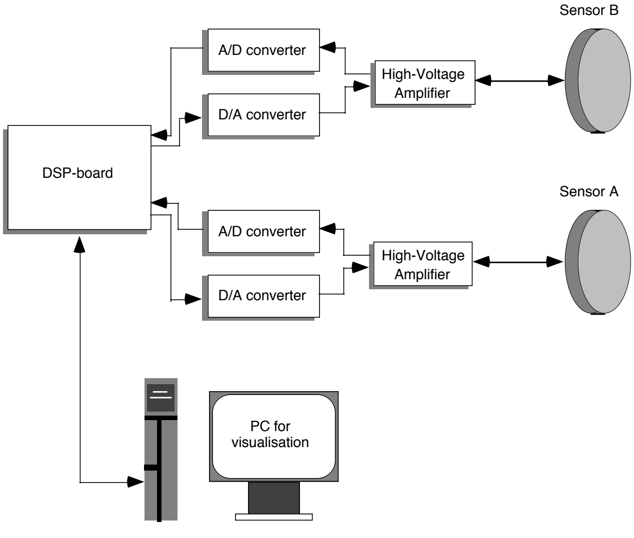


Fig. 3: Experimental platform

voltage swing of 300 V (peak-peak). For the sake of simplicity this voltage is provided by a high-voltage power supply. Alternatively, the OP-amp's power-supply could be generated from a low-voltage PWM circuit [11].

During the receive phase the analog signals provided by both transducers are sampled by a commercially available data-acquisition board [15] and forwarded to the digital signal processor. The DSP then performs the processing of the returns including a Fast Fourier Transformation (FFT) which is an essential prerequisite of any efficient matched filter implementation [3]. The DSP-board is connected to a PC which merely serves as a comfortable user interface.

5 Experimental results

First we would like to point out, that all results presented in this paragraph were achieved by performing physical experiments. In order to obtain good correlation results the choice of the proper reference signal is essential. A reference signal is good if it takes the physical properties of the sensor hardware and its working section (attenuation, filtering, etc.) into account. Thus, instead of using the computed, ideal pseudo-random sequence as a reference we always used a good echo of this pseudo-random sequence. This echo was obtained by performing an individual short-distance reference measurement per transducer prior to the experiment using a strongly reflecting target. Moreover we want to lay particular stress on the fact, that the usable transmitting/receiving frequency ranges of Polaroid's 8000 series transducers are between 40 kHz and 70 kHz which means that the transducer's usable bandwidth is 30 kHz, only. Fig. 4 shows the frequency spectrum of a Polaroid transducer. This spectrum, which was determined by using our experimental platform, limits the bandwidth of the pseudo-random sequences to 30kHz (frequency range: 40kHz - 70kHz). Thus, in order to obtain good correlation results (i.e. to increase the time-bandwidth product) the pseudo-random sequences have to have a sufficient duration. The pseudo-random sequences which were used to obtain the following results had a duration of 2048 µs, each.

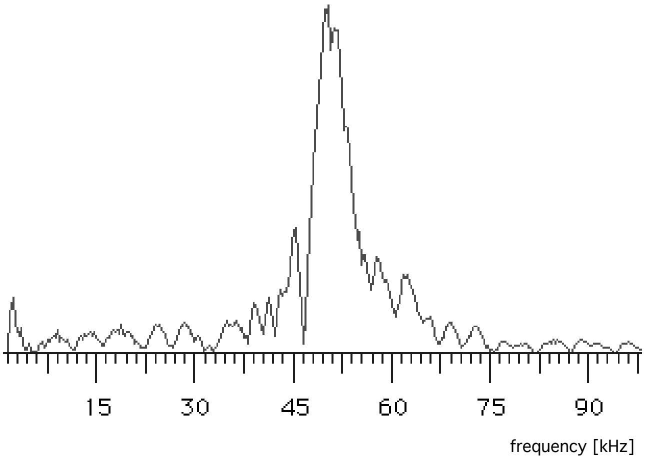
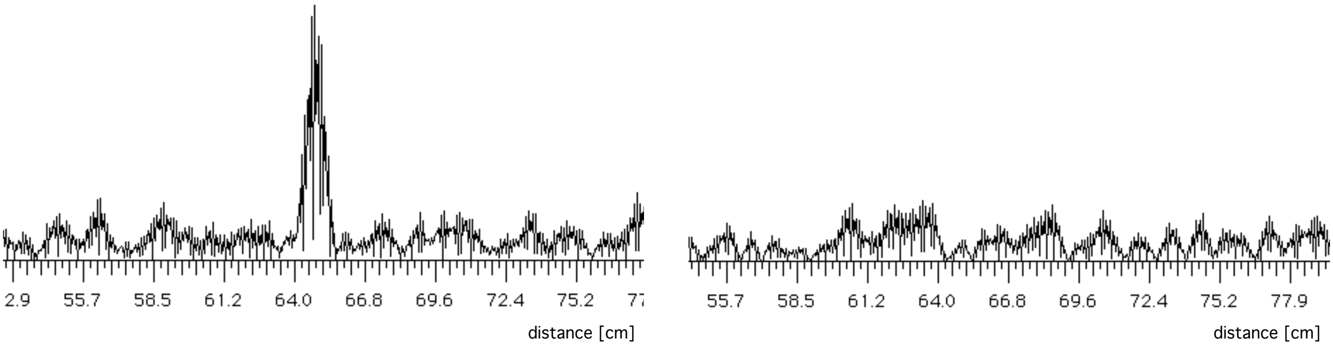


Fig. 4: Frequency spectrum of a Polaroid transducer (8000 series). The usable frequency range is between 40 kHz and 70 kHz.

1. Experiment. The first experiment demonstrates, that the good correlation behaviour resulting from our simulations can be achieved in practice, too. For this purpose the transducers were fired towards the same target one after the other using two different pseudo-random sequences. Thus, the target's echo in the individual returns of each transducer was caused by the pseudo-random se-



a) Sharp autocorrelation function

b) Flat crosscorrelation function

Fig. 5: Correlation behaviour of two pseudo-random sequences

quence of this transducer, only. We then correlated the reference signal associated with transducer A (which was acquired prior to the experiment) with the return received by the same transducer. Fig. 5a shows the correlation result which is indeed a sharp autocorrelation function. Next, we correlated the reference signal of transducer B with the return received by transducer A which led to the flat crosscorrelation function shown in Fig. 5b.

2. *Experiment*. The second experiment is intended to demonstrate that it is possible to fire the transducers simultaneously while each transducer is still able to identify its own echo(es) from the superimposed echo(es) within the return. Both transducers were located approx. 150 cm in front of a wall. Additionally, two plastic pipes (Ø = 5 cm) having a relative longitudinal distance of about 3 cm were positioned in front of the transducers as shown in Fig. 6. The transducers were fired simultaneously using different pseudo-random sequences (40 kHz - 70 kHz, T=2048□µs). Please recall, that it is impossible to distinguish the pipes using CTOF sonar sensing. Fig. 7 shows a screen dump of the transmit/receive cycle of transducer A. The leftmost part of the signal is the pseudo-random sequence transmitted by this transducer while both echoes are a superposition of the pseudo-random sequences of both transducers. Please note, that the first echo is an overlap of the individual echoes of both pipes. Fig. 8 shows the part of the autocorrelation function (correlation of the reference signal of transducer A with the return received by transducer A) referring to both pipes. Please note also, that the small peak on the right hand side refers to a virtual target resulting from a specular reflection between both pipes.

3. *Experiment*. This experiment demonstrates that our approach allows to perform triangulation in order to compensate for a sonar sensor's poor lateral resolution. Fig. 9 shows the experimental setup in which two transducers and two round targets were arranged as illustrated. Both transducers were fired simultaneously using individual pseudo-random sequences. Unlike in the previous experiment the return detected by transducer A was correlated with the references of both pseudo-random sequences, i.e. transducer A is able to determine the round-trip distances *transducer s* → *target t* → *transducer A* with $s \in \{A,B\}$, $t \in \{1, 2\}$.

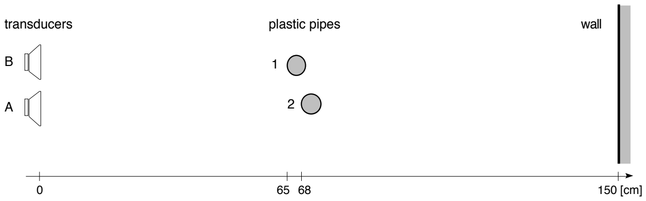


Fig. 6: Experimental setup during the 2. experiment

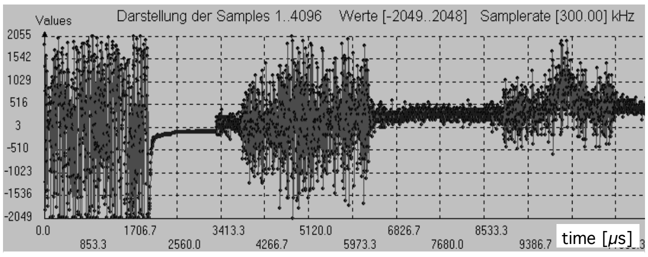


Fig. 7: Screen dump of the transmit/receive cycle of transducer A (2. experiment)

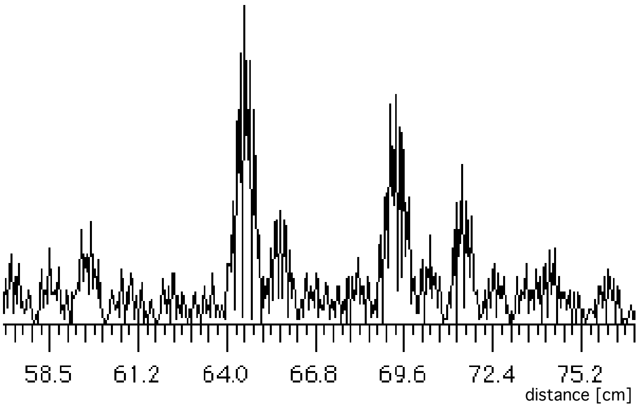


Fig. 8: Part of the autocorrelation function of transducer A refering to the plastic pipes, i.e. to the first echo of Fig. 7 (2. experiment)

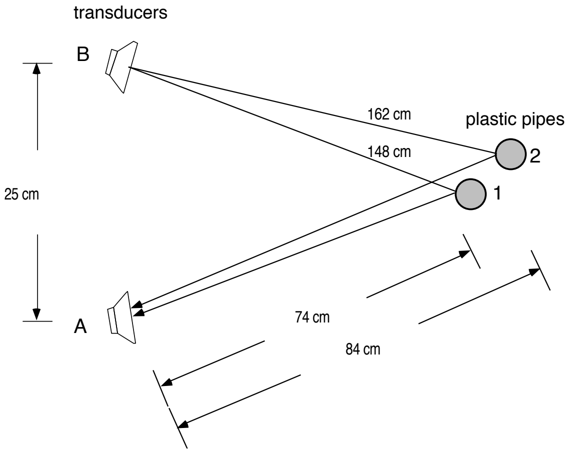
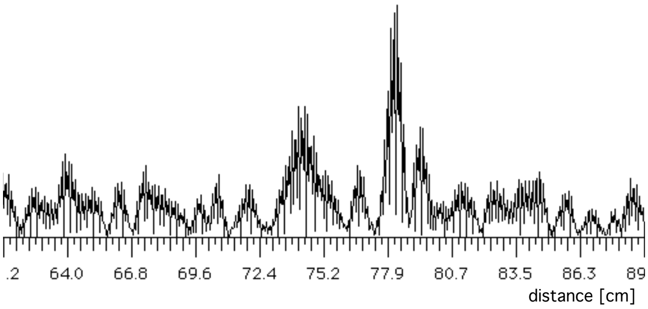
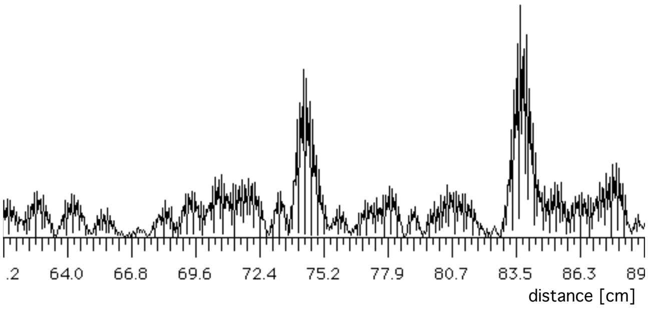


Fig. 9: Experimental setup during the 3. experiment

Fig. 10 shows the correlation results. For each target t, the distance d_t between transducer B and target t is given by the difference of the round-trip distance transducer B → target {1,2} → transducer A and the distance determined by transducer A. Since the distance between both sonar transducers is known the position of each target can be calculated.



a) Correlation with the reference signal of transducer B. Both major peaks correspond to the round-trip distances (transducer B → target {1,2} → transducer A)/2



b) Correlation with the reference signal of transducer A. Both major peaks correspond to the individual distances between transducer A and both targets.

Fig. 10: Correlation of the return detected by transducer A with the references of both transducers pseudo-random sequences (3. experiment)

6 Conclusions

This paper has addressed the crosstalk-problem in mobile robot sonar sensing. A new method was introduced which totally eliminates frequent misreadings caused by crosstalk or external ultrasound sources by applying pseudo-random sequences and a matched filter technique. Additionally, the range resolution as well as the lateral resolution of a sonar sensor are significantly increased. Results from physical experiments were presented.

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