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USING PSEUDO-RANDOM CODES FOR MOBILE ROBOT SONAR SENSING

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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 paper addresses the crosstalk-problem and presents first results of a new approach which enables a mobile robot the simultaneous firing of its sonar sensors. At the same time frequent misreadings caused by crosstalk or external ultrasound sources are eliminated. This is achieved by carefully designing the emitted burst, i.e. by using appropriate pseudo-random sequences together with a matched filter technique. Results from physical experiments are presented.

Keywords: ultrasonic transducers, pseudo-random sequences, correlation, matched filters, mobile robots

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.

Advantages of CTOF sonar sensors are their good availability, their low asset cost and the fact that they can be easily connected to a computer. However, one of the most important advantages compared with active optical range sensing devices is a sonar sensor's property to provide information about volumes of space which is due to the transducers beamwidth.

At the same time the beamwidth is responsible for a sonar sensor's *poor lateral resolution* which is one of its major disadvantages. Other disadvantages include the *limited range resolution* and the proneness to both *specular reflections* and *frequent misreadings*. Moreover, compared to active optical range sensors sonar sensing is slow because of the comparatively low speed of sound in air.

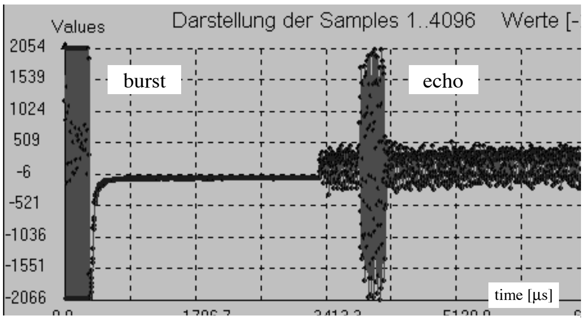


Fig. 1. Transmit/receive cycle of a CTOF sonar sensor

Specular reflections are caused by plain surfaces (provided that the angle of incidence is greater than half the beamwidth) which totally reflect the emitted burst. Thus, specular reflections primarily occur in acoustically hard environments and lead to range readings indicating larger distances than the really existing ones. In (Audenaert, *et al.*, 1992) the authors clearly point out, that specularity is a problem inherent to the medium, not to the sensor. Thus, it is impossible to construct a sensor which is immune to specularity.

Frequent misreadings occur due to either external ultrasound sources or crosstalk. *Crosstalk* is a random error which originates from the use of multiple sonar sensors on a mobile robot and applying a fast firing strategy such as scheduled firing. Depending on the environmental conditions the sonars will mutually influence each other leading to range readings which are generally smaller than the real distances. According to our experience, crosstalk is one of the most crucial problems in mobile robot sonar sensing. If the sonars are for example used to perform collision avoidance it is likely that crosstalk causes the robot to perform a meander-shaped trajectory while avoiding physically not existing obstacles.

This paper primarily addresses the crosstalk-problem and presents promising experimental results of a new approach (Jörg and Berg, 1996) which totally eliminates misreadings caused by external ultrasound sources or crosstalk. This is achieved although the sonars are operated simultaneously. At the same time, our approach comes along with an increased range resolution and serves as a basis to perform triangulation in order to overcome the poor lateral resolution. The approach utilizes mechanisms which are well known from existing radar techniques.

The rest of this paper is organized as follows. The next paragraph presents a brief survey of related work in sonar sensing. Thereafter, paragraph three makes some fundamental remarks on radar basics while paragraph four presents the key-idea of our approach. Paragraph five describes our experimental platform while paragraph six presents results from physical experiments. Finally, paragraph seven describes our future plans together with some concluding remarks.

2. RELATED WORK

In the literature a multitude of papers may be found addressing the problems described above in the context of building up and maintaining sonar-based world models for self-localization, navigation and obstacle avoidance, e.g. (Elfes, 1989), (Borenstein and Koren, 1991), (Buchberger, *et al.*, 1993). Many of these approaches are grid-based, i.e. they interpret each individual sonar range reading by using a specific sonar sensor model, while accepting the first echo per measurement, only. Subsequently, often gridmaps are used to fuse the new environmental information with the environmental knowledge which has been accumulated so far. This process is continued repeatedly hoping to finally obtain complete and reliable world models. Thus, this mechanism is a means to compensate for the inherent limitations of CTOF sonar sensing.

These approaches share the common property that they attempt to a posteriori correct the errors resulting from the straightforward interpretation of the range readings obtained by a CTOF sonar sensor.

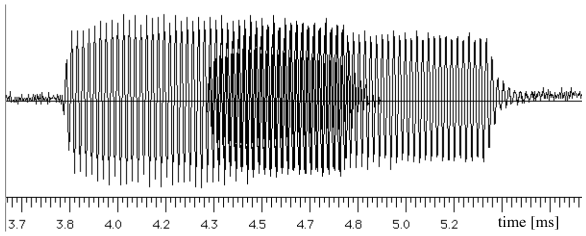
Borenstein and Koren (1992) describe an algorithm for rapid ultrasonic firing of a set of CTOF sonar sensors while rejecting erroneous range readings caused by noise and crosstalk. The algorithm introduces the method of *alternating delays* which is combined with both, the conventional *scheduled firing* scheme and the method of *comparison of consecutive* returns. At this point it is not important to understand how the algorithm works. Instead it is important to realize, that the approach is an attempt to a priori reject erroneous range readings caused by noise and crosstalk. At the same time the algorithm causes a significant speed-up of the firing rate.

Audenaert et al. present a method for the accurate ranging of multiple objects using sonar sensors (Audenaert, *et al.*, 1992). Their approach tries to overcome the limited range resolution of a sonar sensor by applying correlation techniques well known from radar applications. The approach allows to separate consecutive objects having a relative distance of about 2 cm.

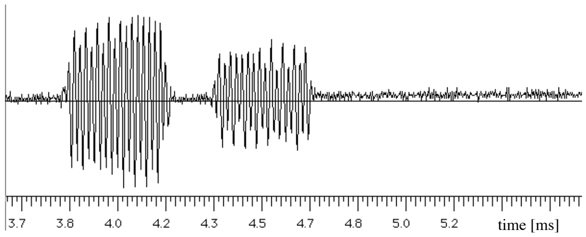
Sabatini and Spinielli (1994) describe a simple ultrasonic pulse-echo ranging system using digital signal processing algorithms which allow an accurate ranging of multiple objects. The algorithms are based on correlation techniques, too.

3. MATCHED FILTER

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 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



a) Overlapping echoes of two consecutive targets (T = 1ms, Δd ≈ 8cm)



b) Non-Overlapping echoes, resulting from a shorter burst (T = 330μs, Δd ≈ 8cm)

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

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 Δd > 16.5cm for T = 1ms (Δd > 5.5cm 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. 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 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 (Fitch, 1988). With a matched filter receiver, the range properties improve as the "time-bandwidth" product of the signal increases. Thus, for any improvements, either 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 can be found e.g. in (Berkowitz, 1967), (Curlander and McDonough, 1991) and (Lüke, 1992).

4. OUR APPROACH - THE KEY IDEA

Against the background of this discussion and the crosstalk-problem mentioned above the key idea behind our approach arose from the consideration

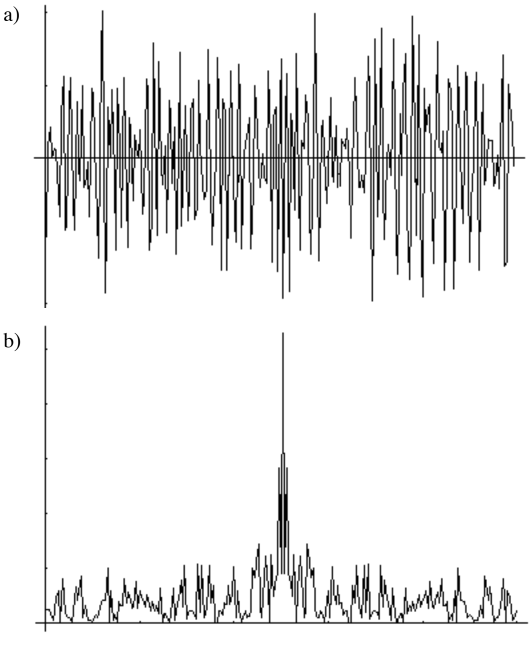


Fig. 3. a) Ideal Pseudo-Random Sequence (30 - 80 kHz), and b) the corresponding autocorrelation function

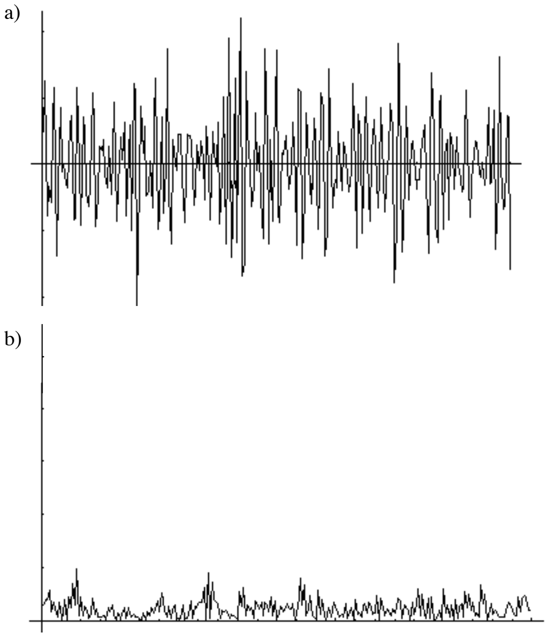


Fig. 4. a) Another ideal pseudo-random sequence (30 - 80 kHz), and b) its crosscorrelation with the sequence of Fig. 3a. Obviously, both pseudo-random sequences do not correlate.

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 (Berkowitz, 1967) it has to be determined experimentally whether or not stochastic signals have good autocorrelation functions. Thus, we performed a series of simulations, first. One result of these simulations was that it is indeed easily possible to find pseudo-random sequences showing the correlation behaviour mentioned above. Fig. 3a shows an ideal pseudo-random sequence with a frequency range of 30 - 80 kHz. Fig. 3b shows the corresponding autocorrelation function which has a significant peak. Fig. 4a shows another ideal pseudo-random sequence with the same frequency range. The correlation of both pseudo-random sequences leads to the crosscorrelation function shown in Fig. 4b. As can be seen easily, both signals do not correlate since there is no significant peak.

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 simulated 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 will be described in the following paragraph.

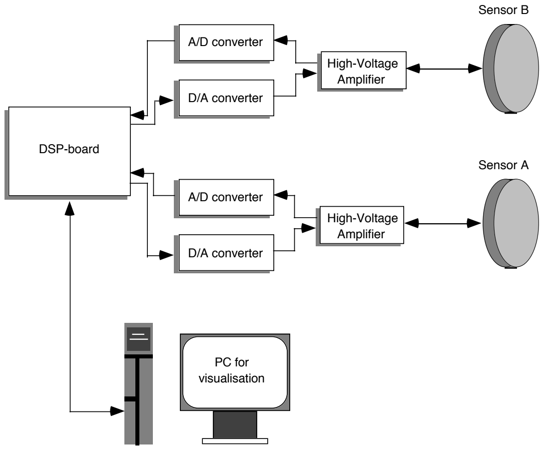


Fig. 5. Experimental platform

5. EXPERIMENTAL PLATFORM

Our experimental platform (Fig. 5) is by the time being 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 (Handbook micro-line CPU44, 1996) 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 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. This technique is used in (Lindstedt, 1996).

During the receive phase the analog signals provided by both transducers are sampled by a commercially available data-acquisition board (Handbook micro-line AD4-612, 1996) 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 (Brigham, 1988). The DSP-board is connected to a PC which merely serves as a comfortable user interface.

6. 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 strong echo of this pseudo-random sequence. This strong echo was obtained by performing an individual reference measurement per transducer prior to the experiment. Moreover we want to lay particular stress on the fact, that the usable transmitting/receiving frequency range of Polaroid's 8000 series transducers is between 40 kHz and 70 kHz which means that the transducer's usable bandwidth is 30 kHz, only (Fig. 6). Thus the pseudo-random sequences have to have a sufficient duration, each, in order to obtain good correlation results. The pseudo-random sequences which were used to obtain the following results had a duration of 2048 µs.

1. Experiment. The first experiment is to demonstrate, that the 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 sequence 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. 7a 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. 7b.

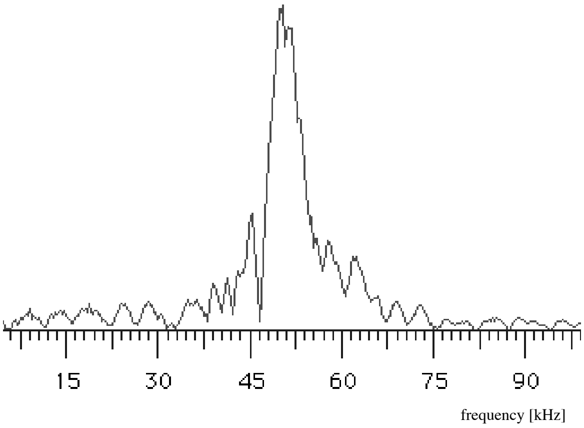
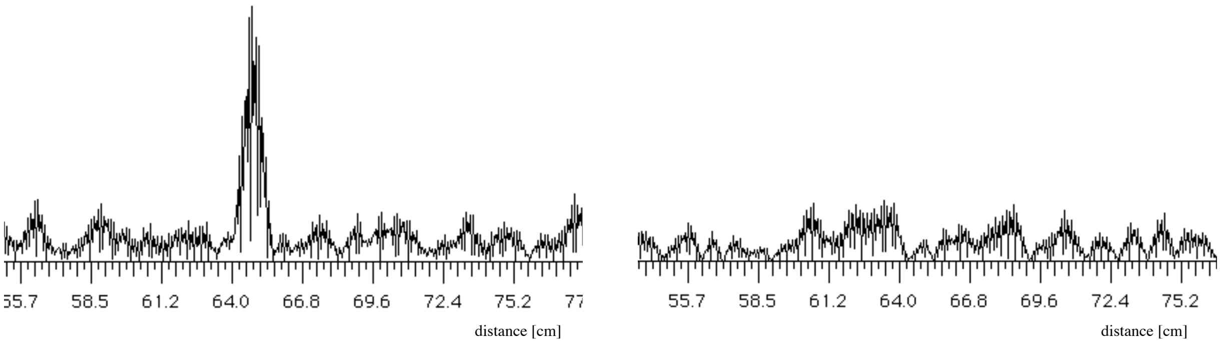


Fig. 6. Frequency spectrum of a Polaroid transducer (8000 series). The usable frequency range is between 40 kHz and 70 kHz.

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. 8. 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. 9 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. 10 shows the part of the autocorrelation func-



a) Sharp autocorrelation function

b) Flat crosscorrelation function

Fig. 7. Correlation behaviour of two (real) pseudo-random sequences

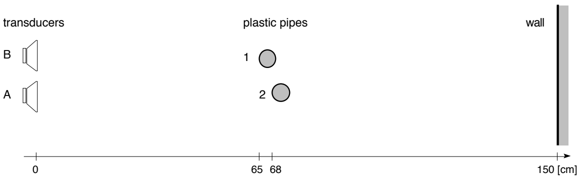


Fig. 8. Experimental Setup during the 2. experiment

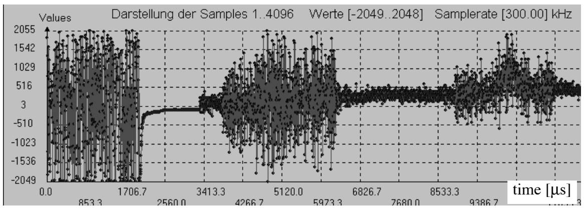


Fig. 9. Screen dump of the transmit/receive cycle of transducer A (2. experiment)

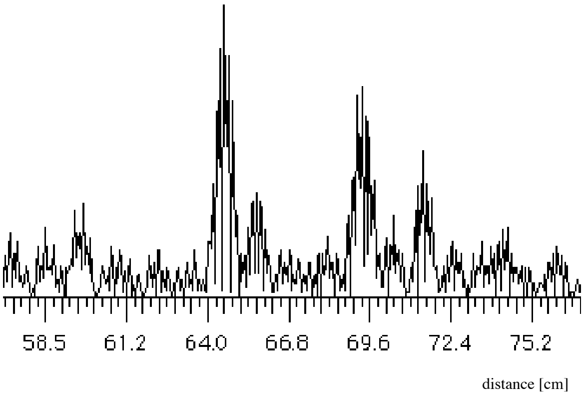


Fig. 10. Part of the autocorrelation function of transducer A refering to the plastic pipes, i.e. to the first echo of Fig. 9 (2. experiment)

tion (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.

7. CONCLUSIONS

These experimental results show that pseudo-random sequences together with a matched filter technique can be used in mobile robot applications in order to eliminate frequent misreadings caused by crosstalk or external ultrasound sources. Since the sonar sensors can be fired simultaneously the approach comes along with an enormous speed-up of the acquisition rate. Additionally, the range resolution is significantly increased. Moreover, one could think of a scenario where the return received by a transducer is not only correlated with this transducer's own pseudo-random sequence but also with the pseudo-random sequences associated with adjacent transducers. This offers the possibility to easily perform triangulation in order to compensate for a sonar sensor's poor lateral resolution.

Compared to CTOF sonar sensing systems, our approach comes along with an increased hardware cost. However, the authors believe that this is acceptable against the background of achieving significantly better results.

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