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First Results in Eliminating Crosstalk & Noise by Applying Pseudo-Random Sequences to Mobile Robot Sonar Sensing

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Abstract

Crosstalk is one of the most severe problems in conventional mobile robot sonar sensing. This paper addresses the crosstalk-problem and presents first and promising results of a new approach which enables a mobile robot to fire its sonar sensors simultaneously while totally eliminating misreadings caused by crosstalk or external ultrasound sources. This is achieved by carefully designing the emitted burst, i.e. by using appropriate pseudo-random sequences together with a matched filter technique. Experimental results are presented.

1. Introduction

Sonar sensors employing the conventional time-of-flight (TOF) principle are widely used within the autonomous mobile robot research community for many years. As reasons therefore their low-cost together with a good availability may be identified as well as the fact, that they can be easily connected to a computer. Another reason might be that in contrast to active optical range sensing devices a sonar sensor due to its beamwidth provides information about volumes of space. That is why sonar sensors are nowadays frequently used for collision avoidance.

However, it is generally known that conventional TOF 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 *poor angular resolution* is due to the transducers beamwidth while the *limited range resolution* depends on the duration of the emitted burst, i.e. if two consecutive objects are closely spaced such that their echos overlap, then they cannot be distinguished.

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 [1], Audenaert et al. 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.

If multiple sonar sensors are used on a vehicle, which is the case in most mobile robot applications, and if these sensors are to be fired as fast as possible (e.g. for fast obstacle avoidance), then the sensors will mutually influence eachother leading to range readings which are generally smaller than the really existing ones. This problem is in the literature referred to as *crosstalk*. According to our experience, crosstalk is one of the most crucial problems in obstacle avoidance using sonar sensors since it causes the robot to perform a meander-shaped trajectory while avoiding physically not existing obstacles.

This paper addresses the crosstalk-problem and presents first and promising results of a new approach which enables a mobile robot to fire its sonar sensors simultaneously while totally eliminating misreadings caused by crosstalk or external ultrasound sources. The approach utilizes mechanisms which are well known from existing radar techniques.

To begin with, the paper's next section presents a brief survey of related work in sonar sensing. Thereafter, section three makes some fundamental remarks on radar basics while section four briefly addresses properties of the matched filter technique. Section five introduces our approach in detail and presents experimental results. Finally, section six describes our future plans while section seven offers 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 [4], [8], [10]. 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 conventional TOF 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 conventional TOF sonar sensor.

In [5], Borenstein & Koren describe an algorithm for rapid ultrasonic firing of a set of conventional TOF sonar sensors while rejecting erroneous range readings caused by noise and crosstalk. The authors state that the algorithm reduces the number of erroneous range readings by one or two orders of magnitude. 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 [1]. 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 & Spinielli describe in [12] 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.

Since these approaches have inspired the work presented here we would like to briefly describe the principal idea behind them in the following paragraph.

3. Fundamental Remarks

It has been mentioned earlier, that the *limited range resolution* of a sonar sensor depends on the width of the emitted burst so that two consecutive, closely spaced objects cannot be distinguished if their echos overlap. Making the burst shorter in duration, will reduce the ambiguity caused by overlapping echos. 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 guarantee non-overlapping echos, objects must be separated in time delay by at least the width of the transmitted pulse. If the burst's duration is T milliseconds, then the time delay between objects must be at least T milliseconds to prevent interference between the echos. 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. Audenaert et al. use a burst in form of a 13 bit Barker codeword which has a very sharp autocorrelation function.

This discussion gives rise to the following question: *Given a ring of 24 sonar sensors, is it possible to design the bursts of these sensors such that each individual sensor is able to separate its own echo from the echos of all the other sensors?* If this were possible, there were no longer a need for applying a firing strategy since all sonars could be operated in parallel which would come along with an enormous speed-up.

We will show in section five that this can be performed by using pseudo-random sequences. Since our approach utilizes a matched filter receiver, this technique is briefly described in the next section.

4. The Matched Filter Receiver

A detailed description of a matched filter receiver is far beyond the scope of this paper and thus omitted - comprehensive descriptions may be found in [7] and [11]. However, we feel that it is important to know that the filter output 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 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.

5. Our Approach: Error Elimination by using Pseudo-Random Sequences

At this point we would like the reader to recall that the scope of this paper is to present a new approach allowing a mobile robot to fire its sonar sensors simultaneously while totally eliminating misreadings caused by crosstalk or external ultrasound sources.

The key idea behind our approach is a very simple one: the emitted 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 it is possible for each individual sonar sensor to identify its own echo by applying a matched filter technique.

One could think of using the Barker code mentioned earlier, which is a pseudo-random binary code satisfying rather stringent autocorrelation behavior. However, the Barker code is not applicable for our purpose since the number of different sequences having the same length is insufficiently small [2].

Instead, we simply use stochastic sequences, i.e. random noise. Since there is no theory to specify the particular autocorrelation of a sequence in advance [2] it has to be determined experimentally whether or not stochastic signals have good autocorrelation functions. Furthermore, it has to be shown that different pseudo-random sequences do not correlate. This will be done in the rest of the paper.

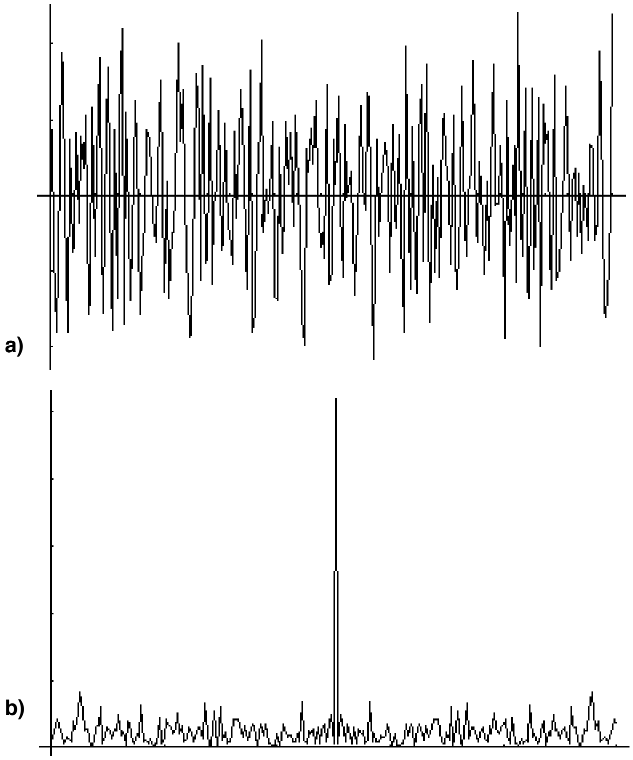


Fig. 1: a) A pseudo-random sequence (0 - 100 kHz) , and b) its autocorrelation function

In order to investigate the autocorrelation properties of random noise we performed a series of simulations. Fig. 1a shows a pseudo-random sequence consisting of 250 values. Having a sample rate of 200 kHz, this is equivalent to a frequency range of 0 - 100 kHz, a duration of the burst of T = 1.25 ms, and a length of the air pressure perturbation of approximately 42 cm (assuming a velocity of sound in air of 335 m/s). Fig. 1b shows the corresponding, very sharp autocorrelation function. We are well aware that this example is far away from reality in so far as the frequency range of ultrasound starts at ≈ 20 kHz. However, the example clearly shows, that pseudo-random sequences indeed can have good autocorrelation properties.

A more realistic example is given in Fig. 2 where the frequency range of the burst is limited to 30 - 80 kHz (Fig. 2a). Fig. 2b shows the corresponding autocorrelation function. In comparison with Fig. 1b, the autocorrelation function of this sequence is less sharp and the signal-to-noise ratio is worse. Nevertheless, a significant peak can be identified. Given a fixed frequency range, other simu-

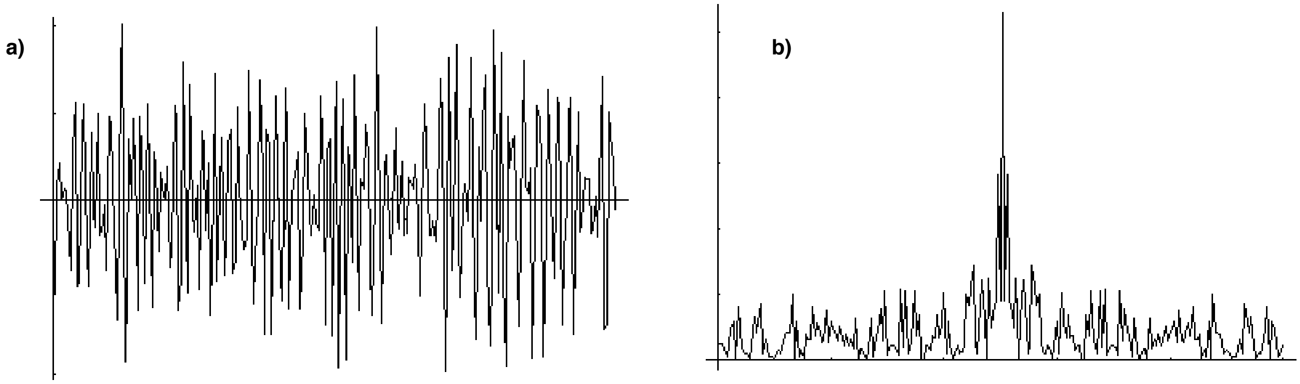


Fig. 2: a) Pseudo-Random Sequence (30 - 80 kHz), and b) the corresponding autocorrelation function

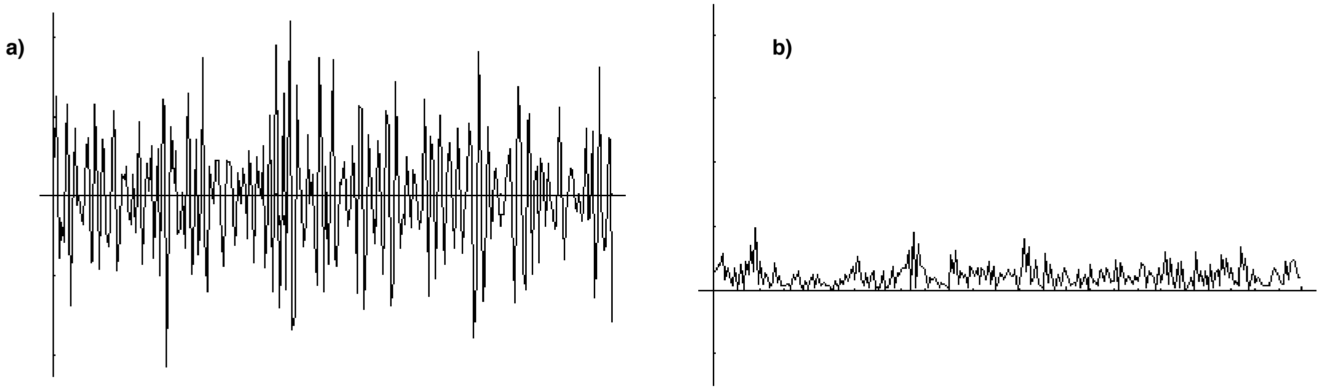


Fig. 3: a) Another pseudo-random sequence (30 - 80 kHz), and b) its crosscorrelation with the sequence of Fig. 2a

lations 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.

Next, we will give an example showing that different pseudo-random sequences usually do not correlate. This example is one out of a series of simulation experiments having had all similar results. Figures 2a and 3a show two different pseudo-random sequences with a frequency range of 30 - 80 kHz and a sample rate of 200 kHz, respectively. The corresponding crosscorrelation function is shown in Fig. 3b. As can be seen easily, both signals do not correlate since there is no significant peak.

From these experiments we claim, that pseudo-random sequences having both, sufficient bandwidth and duration are well suited for error rejection in mobile robot sonar sensing provided that they are properly selected.

The objective of the following, simulated experiment is to demonstrate the advantages of our approach vs. conventional sonar sensor systems. These advantages are as follows:

1. Each sensor S_i is able to identify its own echo. Thus, erroneous range readings caused by crosstalk or external ultrasound sources are reliably rejected.
2. Each sensor S_i is able to identify the echos of all the other sensors. This property offers the possibility to easily perform triangulation in order to compensate for a sonar sensor's poor lateral resolution.
3. The fact, that the approach allows to fire all sonars simultaneously comes along with an enormous speed-up.

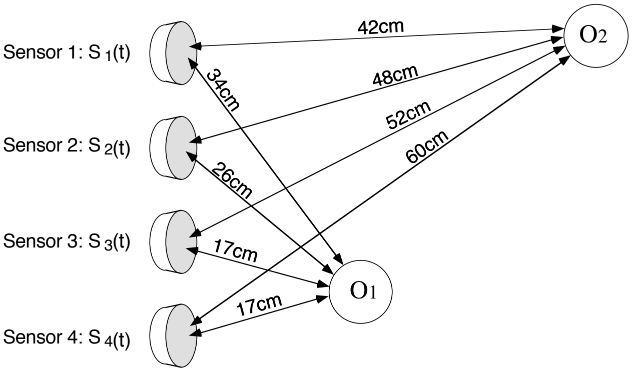


Fig. 4: Experimental setup

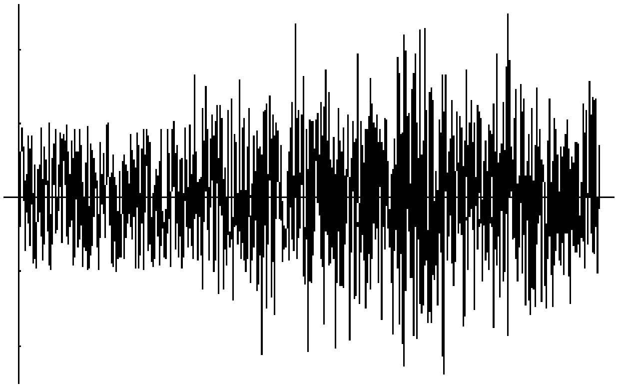


Fig. 5: Superimposed echo, arriving at sensor S_1

Fig. 4 shows the experimental setup in which four sonar sensors and two round objects are arranged as illustrated. It is assumed that the sensors fire simultaneously using individual pseudo-random sequences while both obstacles are detected by each sensor. The parameters are as follows: duration T = 2 ms, frequency range 20 - 90 kHz, sample rate 200 kHz, 400 samples. From the perspective of sensor S_1 this results in an echo, which is a superposition of all eight echos caused by both objects. Fig. 5 shows this superimposed echo, which has additionally been corrupted with noise. For this experiment it is assumed, that each sensor knows not only its own pseudo-random sequence but the pseudo-random sequences of all other sensors, too. Thus, an arbitrary sensor S_x is able to determine the round-trip distances *Sensor* S_i → *Object* O_k → *Sensor* S_x with $i \in \{1,\ldots,4\}$, $k \in \{1, 2\}$ by correlating the received echo with the individual pseudo-random sequences of the other sensors. Fig. 6a-d shows this from the perspective of sensor S_1 using the echo of Fig. 5. Thus, triangulation can easily be performed.

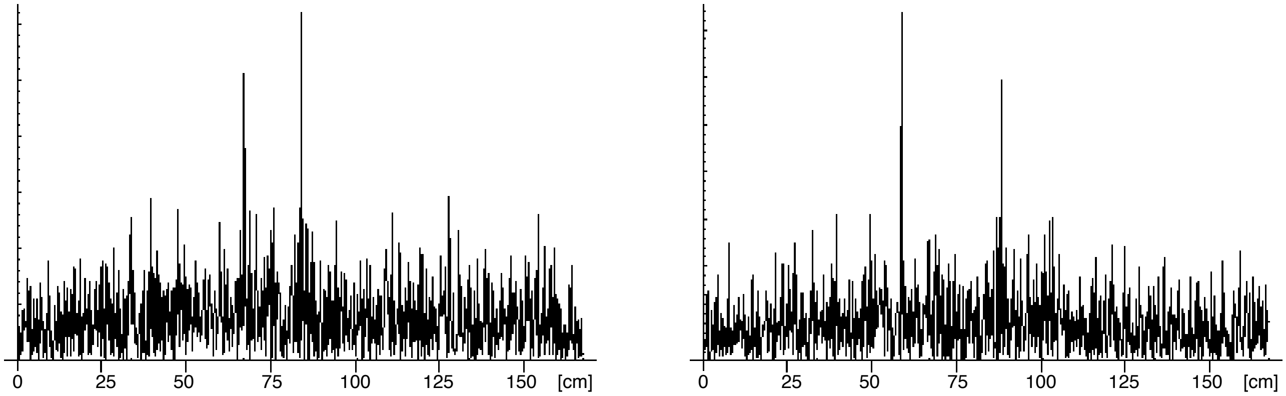
Although our results are very promising, we need to answer the question of how many sensors may be fired simultaneously such that their individual returns can be reliably separated. This question arises from our expectation that the superposition of a multitude of echos finally provokes that an individual sonar sensor may not longer be able to identify its own echo. However, several tests simulating up to 24 simultaneously arriving echos from arbitrary pseudo-random sequences (assuming the configuration of Fig. 4) have shown that it is in principal possible to identify an individual echo. We expect that this problem is of a minor significance on a real mobile robot where the sonar sensors are normally arranged as a ring around the vehicle. Thus, it is very likely that incoming echos are a superposition of a subset of all bursts, only.

6. Future Work

Currently we are trying to verify the results presented in this paper using real sonar sensors. In order to achieve this goal we are designing a specific sonar sensor hardware which supports both, the transmission of pseudo-random sequences and the sampling of the echos. Since a Fast Fourier Transformation is an essential prerequisite of any efficient matched filter implementation [3], we plan to utilize a DSP hardware for this purpose.

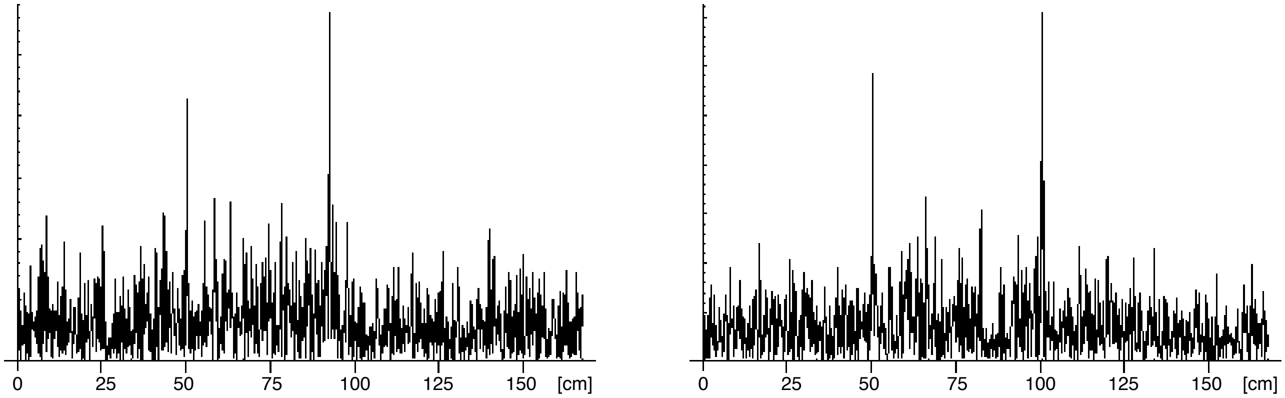
7. Conclusions

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. We want to point out clearly, that not all pseudo-random sequences have autocorrelation functions which are as good as the one shown in Fig. 2b. However, it is possible to a priori select pseudo-random sequences which are optimal in the sense that each one has a sharp autocorrelation function while two arbitrary pseudo-random sequences do not correlate, i.e. each sensor gets its fixed, individual pseudo-random sequence. Since the results presented here, which were obtained theoretically by performing appropriate simulations are indeed very promising, the authors expect to achieve an equivalent performance using real sensors. Compared to conventional TOF sonar sensing systems, the approach comes along with an increased hardware cost. However, the authors believe that this increased cost is justified against the background of achieving significantly better results.



a) **Sensor S_1 → Object $O_{\{1,2\}}$ → Sensor S_1**

b) **Sensor S_2 → Object $O_{\{1,2\}}$ → Sensor S_1**



c) **Sensor S_3 → Object $O_{\{1,2\}}$ → Sensor S_1**

d) **Sensor S_4 → Object $O_{\{1,2\}}$ → Sensor S_1**

Fig. 6: Correlation results (the left peaks correspond to O_1, and the right peaks to O_2, respectively)

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