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Towards Sophisticated Mobile Robot Sonar Sensing using Pseudo-Random Sequences

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Abstract

Conventional time-of-flight (CTOF) sonar sensing is widely used within the autonomous mobile robot research community. One of its most severe problems is known as crosstalk. This paper presents first experimental results of a new approach which allows to operate a set of sonar sensors simultaneously. Nevertheless, frequent misreadings caused by crosstalk or external ultrasound sources are eliminated. This is achieved by carefully designing the emitted bursts, i.e. by using appropriate pseudo-random sequences together with a pulse compression technique well known from radar applications.

1 Introduction

In conventional time-of-flight sonar sensing, 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 *misreadings* due to external ultrasound sources. 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.

From the literature a variety of approaches is known which try to a posteriori correct the errors resulting from the straightforward interpretation of the range readings obtained by a CTOF sonar sensor system, e.g. by using grid-based techniques [4], [6]. In [5] an algorithm for rapid ultrasonic firing of a set of CTOF sonar sensors is presented which is a first attempt to a priori reject erroneous range readings caused by noise and crosstalk.

This paper addresses the crosstalk-problem and presents first experimental results of a new approach [10] which allows to operate a set of sonar sensors simultaneously. In mobile robot applications this comes along with a considerable speed-up. At the same time, misreadings caused by crosstalk or external ultrasound sources are eliminated.

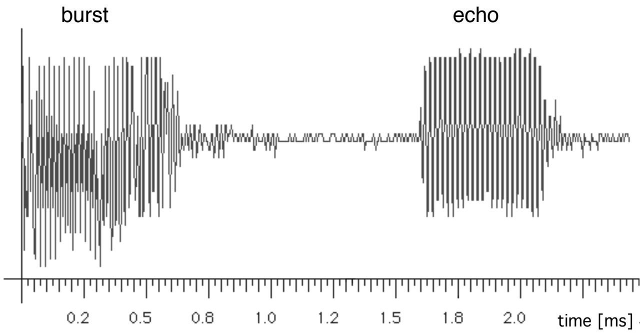

Fig. 1: Transmit/receive cycle of a CTOF sonar sensor

Our approach was inspired by the work presented in [1], [11], and [14]. It utilizes mechanisms which are well known from existing radar techniques.

2 Pulse Compression & Matched-Filter Receiver

Using CTOF sonar sensing, two or more consecutive targets 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. 2 examplifies these circumstances. It shows an emitted burst and the echoes of 4 consecutive targets. Echo 2 and echo 3 overlap since the relative distance Δd of the targets 2 and 3 is smaller than cT/2 (c: speed of sound). 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. Nevertheless, as long as the burst has some width there will be some minimum time delay between targets 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. 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, e.g. a linear frequency-modulated signal or a Barker codeword [1]. The separation of multiple objects is achieved by processing the return using e.g. a matched filter receiver and applying a peak detection algorithm. From radar this technique is known as *pulse compression* [2]. The output of a matched filter receiver is a measure of how precisely the received signal and a reference match. Under the condition that the emitted burst has a sharp autocorrelation function it can be proven that the matched filter is statistically the optimum filter for performing this operation [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. Comprehensive descriptions of a matched filter receiver may be found in [7] and [13].

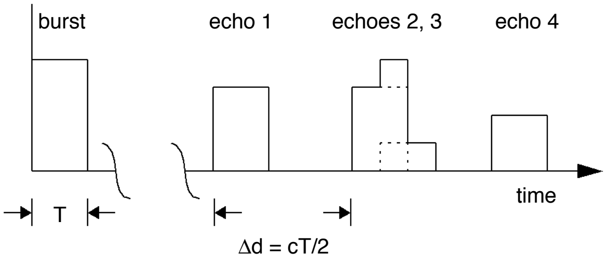

Fig. 2: Overlapping echoes

Since pulse compression is obviously useful to increase a sonar sensor's limited range resolution, at this point of our discussion the question may arise in the reader's mind of how this technique is related to the crosstalk problem addressed in this paper. The following, central question is intended to light up this relation:

Given a set of identical sonar sensors which share a common frequency range. Is it possible to design the bursts of these sensors such that each individual sensor is able to separate its own echo from the echoes of all the other sensors?

If this could be achieved, the sonars of a mobile robot could be operated in parallel and at the same time misreadings caused by crosstalk or external ultrasound sources would be eliminated.

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

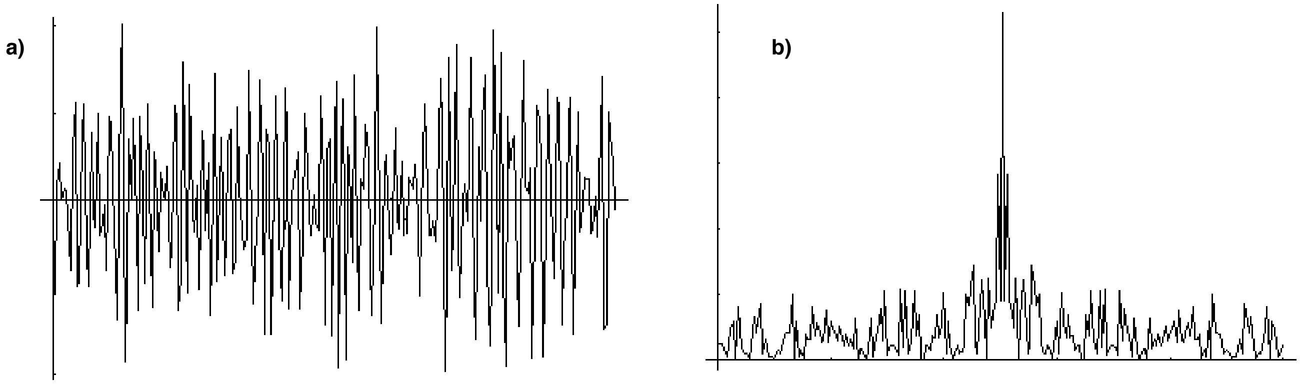

Fig. 3: a) Pseudo-Random Sequence (30 - 80 kHz), and b) the corresponding autocorrelation function

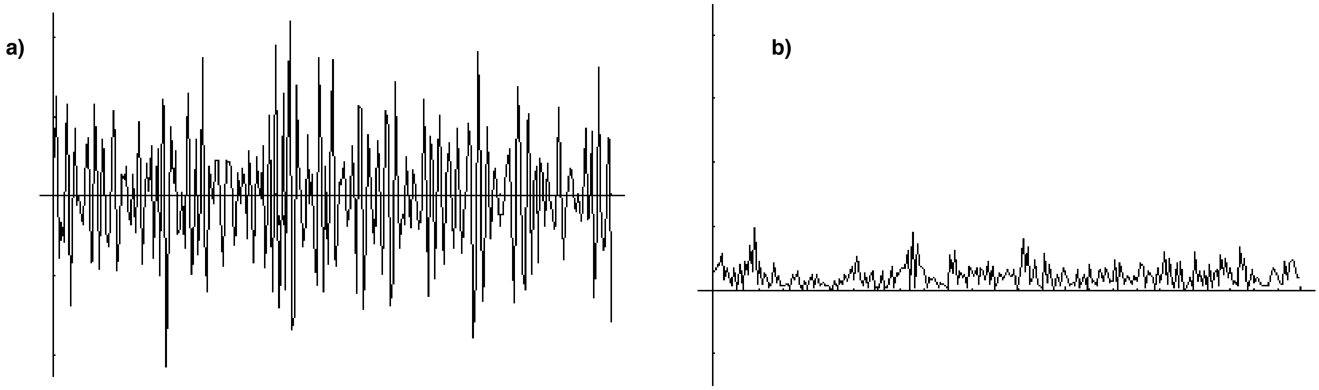

Fig. 4: a) Another pseudo-random sequence (30 - 80 kHz), and b) its crosscorrelation with the sequence of Fig. 3a

own echo(es) by autocorrelation. However, this is not possible for more than two sensors.

We will show in the following that the goal defined by the beforementioned central question can be achieved by applying pseudo-random sequences.

3 Applying Pseudo-Random Sequences

The key idea behind our approach is as follows: the emitted burst of each individual sonar sensor is a pseudo-random sequence, i.e. random noise. 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.

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. One result of these simulations was that it is indeed possible to find pseudo-random sequences showing the correlation behaviour mentioned above. Fig. 3a shows a 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 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 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 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.

4 Experimental platform

Our experimental platform is at the moment 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 [15] 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 by Lindstedt [12].

During the receive phase the analog signals provided by both transducers are sampled by a commercially available data-acquisition board [16] 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 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 emphasize, 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. 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 (see Fig. 3 & Fig. 4) 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. 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) with-

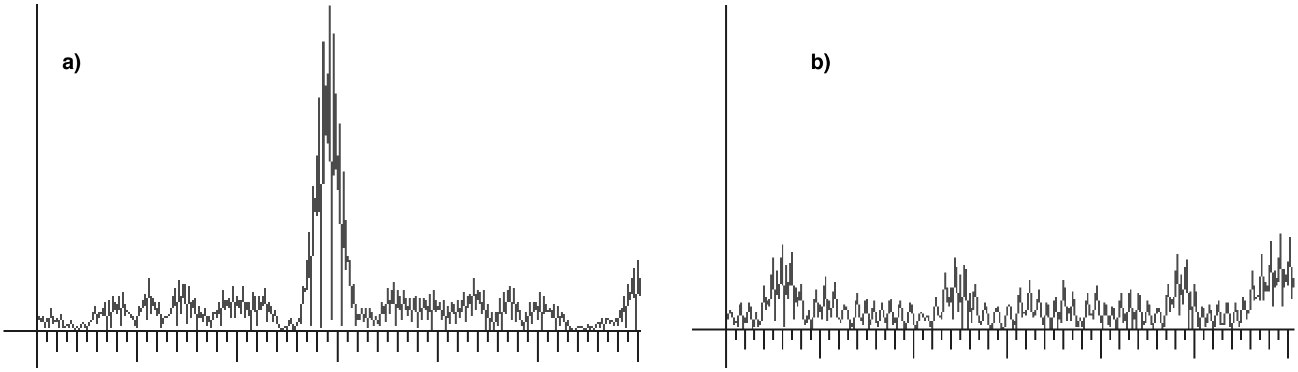

Fig. 5: a) Real autocorrelation function **b) Real crosscorrelation function (same scale)**
These results were obtained by using real pseudo-random sequences (40 - 70 kHz, T = 2048 µs)

in 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 = 2048µs). 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. Thus, the first echo refers to both plastic pipes while the second echo refers to the wall.

Moreover, 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.

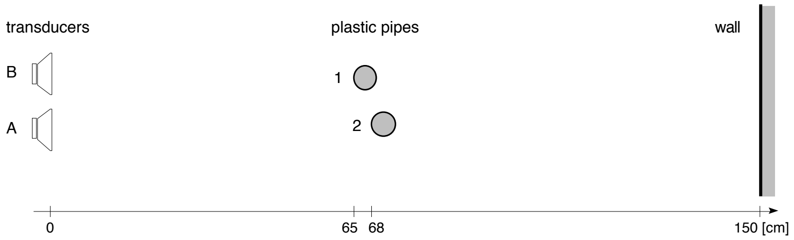

Fig. 6: Experimental Setup during the 2. experiment

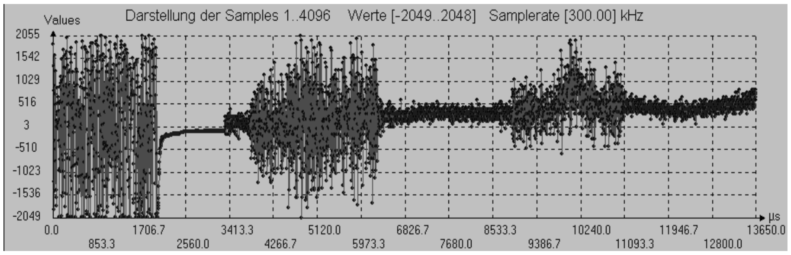

Fig. 7: Screen dump of the transmit/receive cycle of transducer A (2. experiment)

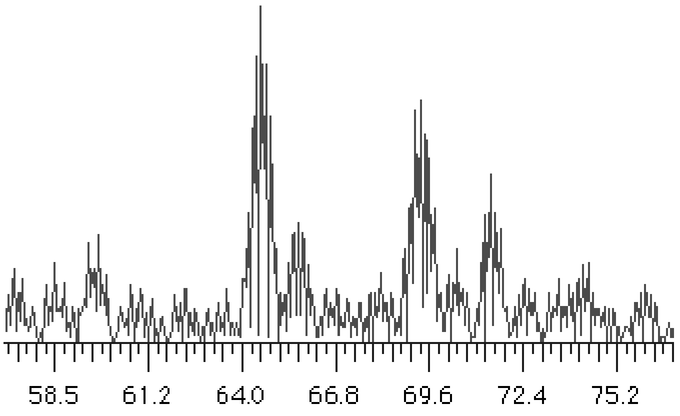

Fig. 8: Part of the autocorrelation function of transducer A refering to the plastic pipes, i.e. to the first echo of Fig. 7 (2. experiment, distances in [cm])

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 misreadings caused by crosstalk or external ultrasound sources. Since the sonar sensors can be fired simultaneously the approach comes along with a considerable 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 [10].

6 Conclusions

The crosstalk-problem in mobile robot sonar sensing has been addressed. A new approach was introduced which eliminates misreadings caused by crosstalk or external ultrasound sources. The approach is based on the careful design of each transducer's individual burst such that the corresponding echoes can be identified by using a matched filter receiver. It was demonstrated that pseudo-random sequences are well suited for this purpose. Experimental results were presented.

Compared to conventional TOF 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.

References

[1] Audenaert, K.; Peremans, H.; Kawahara, Y.; Van Campenhout, J.: *Accurate Ranging of Multiple Objects using Ultrasonic Sensors*, Proceedings of the 1992 IEEE International Conference on Robotics and Automation, Nice, France, 1992

[2] Berkowitz, R.S. (Ed.): *Modern Radar - Analysis, Evaluation, and System Design*, John Wiley & Sons, Inc., 1967

[3] Brigham, E.O.: *The Fast Fourier Transform and its Applications*, Prentice-Hall, 1988

[4] Borenstein, J.; Koren, Y.: *Histogramic In-Motion Mapping for Mobile Robot Obstacle Avoidance*, IEEE Transactions on Robotics and Automation, Vol. 7, No. 4, August 1991

[5] Borenstein, J.; Koram, Y.: *Noise Rejection for Ultrasonic Sensors in Mobile Robot Applications*, Proceedings of the 1992 IEEE International Conference on Robotics and Automation, Nice, France, 1992

[6] Buchberger, M.; Jörg, K.W.; von Puttkamer, E.: *Laserradar and Sonar Based World Modeling and Motion Control for fast Obstacle Avoidance of the Autonomous Mobile Robot* MOBOT-IV,Proceedings of the 1993 IEEE International Conference on Robotics and Automation, Atlanta, Georgia, 1993

[7] Curlander, J.C.; McDonough, R.M.: *Synthetic Aperture Radar - Systems and Signal Processing*, John Wiley & Sons, 1991

[8] Elfes, A.: *Using Occupancy Grids for Mobile Robot Perception and Navigation*, IEEE Computer 6/89

[9] Fitch, P.J.: *Synthetic Aperture Radar*, Springer-Verlag, 1988

[10] Jörg, K.W.; Berg, M.: *First Results in Eliminating Crosstalk & Noise by Applying Pseudo-Random Sequences to Mobile Robot Sonar Sensing*, Proceedings of the 1st Euromicro Workshop on Advanced Mobile Robots (EUROBOT'96), Kaiserslautern, Germany, IEEE Computer Society Press, 1996

[11] Lindstedt, G.: *Borrowing the Bat's Ear for Automation - Ultrasonic Measurements in an Industrial Environment*, PhD Thesis, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund, Sweden, 1996

[12] Lindstedt, G.: *Recognition using Frequency Sweep Sonar*, Proceedings of the 1st Euromicro Workshop on Advanced Mobile Robots (EUROBOT'96), Kaiserslautern, Germany, IEEE Computer Society Press, 1996

[13] Lüke, H.D.: *Signalübertragung - Grundlagen der digitalen und analogen Nachrichtenübertragungssysteme*, Springer-Verlag, 1992

[14] Sabatini, A.M.; Spinelli, E.: *Correlation Techniques for Digital Time-of-Flight Measurement by Airborne Ultrasonic Rangefinders*, Proceedings of the IROS '94, Munich, Germany, 1994

[15] *Handbook micro-line C44CPU*, Orsys Orth System GmbH, Markdorf, Germany, 1996

[16] *Handbook micro-line AD4-612*, Orsys Orth System GmbH, Markdorf, Germany, 1996