3D TRACKING SONARS WITH HIGH ACCURACY OF RANGE MEASUREMENTS FOR AUTONOMOUS MOBILE ROBOT NAVIGATION

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ABSTRACT

An array of in-air sonar sensors using correlation techniques for range estimation is developed for accomplishing object identification and location in the 3D space; the intended applications are mainly in the field of autonomous mobile robot navigation.

A major emphasis in this paper is given to the concept of the baseband equivalent receiver which is proposed for designing digital correlators of low complexity. Thanks to the combination of analog multiplexing and second order bandwidth sampling techniques, the baseband equivalent receiver we propose proves to be a valuable concept for designing a novel class of tracking sonar devices.

1. INTRODUCTION

Acoustic sensing techniques are widely used in the field of advanced robotics and flexible industrial automation as a means for determining the proximity of objects. In spite that optical sensing techniques are also available for solving similar perceptive problems, the spatial understanding provided by simple-to-use and inexpensive ultrasonic sensors is of great relevance in a variety of applications, including both autonomous robot vehicles and manipulators.

Nonetheless, the field of ultrasonic imaging in air, by far the propagation medium of major interest in robotic applications, is still in its infancy, especially if the state-of-the-art of airborne ultrasonics is compared to that reached in other application domains, i.e. diagnostic imaging and nondestructive evaluation. The reasons for explaining this situation are twofold: on one hand, the hydiosincracies of ultrasonic waves propagating in air make the interpretation of sonar range data a difficult problem; on the other hand, ease of installation, low cost of hardware components, and fast processing are the most appealing features of acoustic sensing techniques. Because of that, the sonar ranging systems proposed for use in laboratory prototypes or commercial robots are rather crude, since the desired range measurements are typically performed using simple and inexpensive analog signal processing techniques [1]. Recently, a few research groups around the world are attempting to design and fabricate more sophisticated systems [2]-[4].

Our present research efforts are aimed at designing sonar ranging systems of novel conception, where more sophisticated range estimation methods than those used in the vast majority of current sonar ranging systems are not necessarily accompanied by a great increase in the complexity of the system requirements, in terms of sampling rates, memory, and computation time. In the coded excitation sonar ranging system described in this paper, highly accurate range measurements are achieved by means of correlation techniques. A modified bandwidth sampling technique, combined with analog multiplexing of the return signals, is conceived for allowing the incorporation of a number of receiving transducers into the system. Simple algorithms for data trilateration both in the azimuth amd elevation directions can be exploited for performing 3D location and identification of a few specular and diffractive targets, which are typically present in those indoor environments of main interest in the field of mobile robot navigation [5]-[6].

2. THEORY OF OPERATION

The problem of estimating a time delay can be cast in the general framework of time-localisation of the global peak of a particular correlation function. The assumptions for the validity of the approach are verified at first approximation for applications in the robotic field. In particular, most objects in the real world present a mirror-like behaviour because of the relatively long acoustic wavelengths of impinging ultrasonic waves [5]. Hence, several objects do not change appreciably the shape of the return echoes, so as we can reasonably assume that the return signal r(t) is a time-delayed, scaled replica of a reference waveform s(t):

$$r(t) = \alpha\, s(t - \tau) + n(t) \tag{1}$$

where τ is the time-of-flight (TOF) existing between the sensor and the insonified object, placed at a distance R from the sensor:

$$\tau = \frac{2R}{c} \tag{2}$$

Here c is the speed-of-sound value in air (c≈346 m/sec at the ambient temperature T=24°C). Under the assumption that the noise n(t) superimposed on the signal s(t) is white Gaussian, an optimal TOF estimator is given by the time instant when the correlation function between the return signal and the reference waveform takes its maximum value:

$$\hat{\tau} = \operatorname{argmax}\left[\int_{-\infty}^{+\infty} r(t)\, s(t+\tau)\, dt\right] \tag{3}$$

3. DESIGN OF A BASEBAND RECEIVER

A great change in the signal bandposition takes place when the so-called complex envelope is used to represent a narrowband signal, especially for those signals with small fractional bandwidths such as the ones produced from in-air sonar sensors. The implementation of a digital correlator which correlates the complex envelopes of the involved signals is attractive in computational terms; moreover, since the bandpass correlation functions of narrowband signals present an oscillatory behaviour, with many peaks of almost the same value, loss of resolution may arise in the process of searching for the global maximum. This problem does not exist with a baseband correlation function, because of the removal of the carrier component.

3.1 Second order bandwidth sampling technique

A simple means for getting the complex envelope from the samples of a narrowband signal is given by the adoption of a second-order bandwidth sampling tehcnique. The technique relies on the use of two separate sampling trains at a rate consistent with the signal bandwidth B:

$$f_s = \frac{2 f_0}{n} \geq B \tag{4}$$

The two sampling trains are time-delayed relative to each other by the fixed quantity:

$$v = \frac{1}{4 f_0} \tag{5}$$

yielding two data channels which provides us with, respectively, the samples of the in-phase and quadrature components of the signal to be sampled:

$$\begin{aligned} s_1(kT_s) &= (-1)^{kn}\, s_I(kT_s) \\ s_2(kT_s + v) &= (-1)^{kn+1}\, s_Q(kT_s + v) \end{aligned} \tag{6}$$

Our approach for implementing the described sampling technique consists of using only one A/D converter; the converter runs at the rate $4f_0$ and it is synchronised to the leading edge of the transmission pulse. Since the complex envelope is sampled at a rate $2f_0/n$, doublets of samples from the desired signal can be taken, so as to leave some gaps in the sampling comb. These gaps can be filled by doublets pertaining to other sampled signals if analog multiplexing techniques, properly interlaced to the sampling process, are used to feed the A/D converter with the desired signals. Hence, the adoption of a given decimation factor n corresponds to place an upper bound on the number m of receiving transducers that can be handled via a single A/D converter (m=n).

3.2 Fractional delay filter

A problem with the proposed technique is that the time instants when we know the in-phase component differ from the time instants when we know the qudrature component, because of the inherent delay existing between the two data streams at the output of the sampler. It is straigthforward to demonstrate that a serious consequence of neglecting the time delay in the reconstruction of the correlation function is given by the fact that the time delay estimate becomes biased. This bias is somewhat "triggered" by the randomly varying echo sampling phase; normally, the echo sampling phase adds a pure phase term to the baseband correlation function, which is without any consequence in practice, since the time delay estimate is derived from the modulus of the correlation function. In the presence of a delay between the in-phase and quadrature components, however, the echo sampling phase affects the correlation function. Fast and simple interpolation techniques can help in recovering the correct time alignment between the in-phase and the quadrature component. The second order Lagrange interpolation formula applied to the quadrature component samples of each sampled signal allows for almost entirely removing the bias otherwise occuring in the corresponding time delay estimates.

3.3 Deconvolution of the sensor impulse response

In our approach, the correlator reference waveform is modified in order to incorporate an inverse filter into the receiver structure. Such a filter is designed according to the algorithm proposed in [8], and its aim is to enlarge the available sensor bandwidth. The correlator reference waveform R(f) has thus to be modified as follows:

$$R(f) = R(f)\,|H_{inv}|^2 \tag{7}$$

Since the transmit signal is formed by a Barker-coded carrier at frequency f_0 (the transducer operating frequency), the inverse filter allows us to use a relatively small number L of carrier periods per code bit (L=4), without incurring in a significant enhancement of the sidelobe levels of the correlation function over the theoretically predictable levels; otherwise, we should be forced to use transmit signals of longer duration ($L \geq 6$). Transmit signals of lesser duration are important to decrease the minimum sensing range.

3.4 Computing the correlation function

The computation of the correlation functions is done in the frequency domain, using Fast Fourier Transform (FFT) techniques. Since linear correlations have to computed, an upper bound on the maximum sensing range of the tracking sonar device must be considered; such a bound depends on the FFT size, the length of the correlator reference waveform, and the baseband sampling interval. Parabolic interpolation techniques are finally used to avoid the loss of resolution of the time delay estimates, otherwise occurring when working with sampled signals.

4. EXPERIMENTAL RESULTS

A prototype of the proposed tracking sonar device has been implemented in our lab, using one transmitter and m receivers (m=4). The transducers are piezoelectric capsules (Mod. MA40B5R/S, Murata, Kyoto, Japan), with an operating frequency f_0=40 kHz. The baseband sampling frequency is therefore f_s=20 kHz. 2n=8 FFTs of length K=512 are computed for a maximum sensing range of about R_{max}=4m. L=4 carrier cycle per code bit are used with a 13bit-long Barker code to form the transmit signal; this implies a duration of the transmit signal of about 1.3 msec, for a minimum sensing range of about R_{min}=20 cm.

The experimental platform is built around a PC486DX, the host computer where we develop and test the algorithms for acoustic imaging, object recognition, extraction and tracking of acoustic landmarks. These applications capitalise on the ability of the tracking sonar to perform highly accurate range measurements. A block diagram of the developed system is shown in Fig.1.

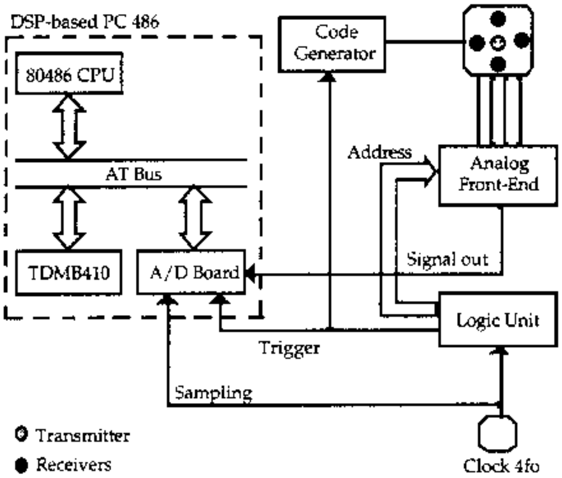

Fig. 1 Block diagram of the experimental system

A TIM-40 motherboard for PC-AT class machines (Mod. TDMB410, Transtech Parallel Systems Corp., Itaha, NY) is plugged into the host computer. The motherboard contains a single TMS320C40 DSP chip (Texas Instruments Corp., Houston, TX). This processor is used as a sort of math coprocessor in place of the native coprocessor the PC comes equipped with. All the computationally intensive operations needed to achieve the desired range estimates are executed by the DSP coprocessor and transferred to the host computer at the end of each measurement cycle. The design of the transmitter module is simplified by considering a square wave carrier; the filtering of the high-frequency harmonic content of the resulting transmit signal is performed by the narrowband transducer itself. A separate acquisition board is used for data collection; after data have been acquired, a DMA transfer takes place to the DSP memory banks, where the data are reorganised to build the complex envelopes of each measuring channel. For each receiving transducer, the reference waveform is separately evaluated, so as to compensate for those minor variations of the sensor physical properties which may arise between otherwise nominally identical sensors. The complex-valued FFT of the reference waveforms are computed off-line once for all, and downloaded into the DSP RAM banks during the booting phase.

The sensor array has been calibrated as for its capability to perform range measurements. Since the reference waveforms are computed separately for each receiving transducer, the offsets in the range measurements can be compensated for almost entirely. The results of sensor calibration are reported in Fig. 2 for a specific receiver, where the distance uncertainty combines bias and standard deviation for each value of the Signal-to-Noise ratio (SNR) over a sample of 1000 consecutive measurements. No significant differences are seen between the various measuring channels of the tracking sonar device.

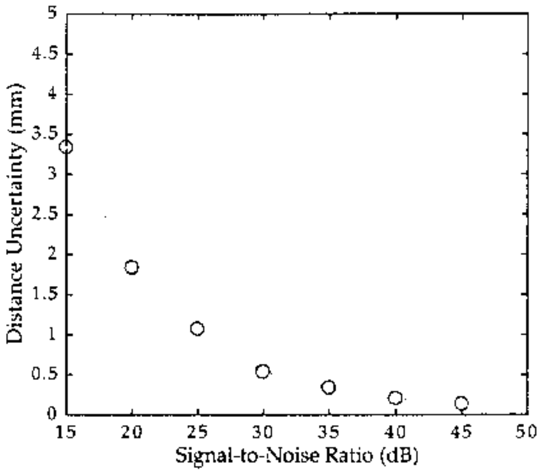

Fig.2: Results of sensor calibration.

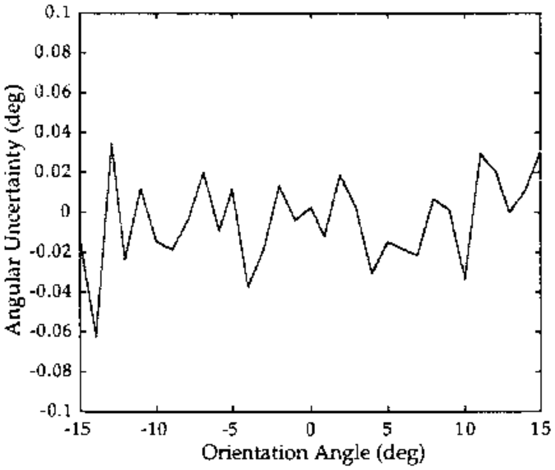

Fig.3: Angular uncertainty of a planar surface.

Because we are currently unable to place a given target at a precisely controlled distance from the sensor beyond the sensing range of one meter, the measuring ability of the system is assessed according to the following protocol: the distance is kept fixed, and the energy of the transmit signals is modified, with concomitant SNR variations at the receiver input. The fixed distance is settled at 50 cm.

The orientation of a vertical planar surface at a distance of about D=1.5 m is finally estimated using the lateral array transducers. The orientation is precisely settled by arranging the sensor array on top of a rotary slide. An angular scan of extent $\beta = 30°$ and step $\Delta\beta = 1°$ is performed and the orientation estimates are derived from the raw range data extracted at each sensing position during the scan.

Acknowledgments

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