Trade-offs in the Design of Ultrasonic Speed Measurement Methods

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Abstract— **This paper presents the results of a study on speed measurement based on the use of the Doppler effect for a 3-D ultrasonic tracking system. Several methods in the state-of-art techniques for speed estimation have been considered, including the unwrapping angle method, zero padding, the Eigenvector method, the Burg method, the multiple-signal classification (MUSIC) method and the use of the 'estimation of signal parameters via rotational invariance technique' (ESPRIT). The influence of various parameters, such as the Signal-to-Noise Ratio, the sampling frequency, the observation time, and the number of samples, for measurement resolution has been evaluated. A comparison of the resolution and the errors for the various methods has been presented and experimentally verified.**

In a test set-up, using a fixed position of the objects, with the ESPRIT method and a SNR of about 30 dB and a test time of 770 μs, the resolution in speed estimation amounts to about 0.03 m/s.

Keywords— **Doppler effect, non-parametric techniques, parametric techniques, ESPRIT, Ultrasonic.**

I. INTRODUCTION

Speed measurement can be implemented using various measurement techniques. Once the position is measured, it would be easy to calculate the speed as the derivative of the position. However, the disadvantage for this approach is, that for a fast speed measurement, a high update rate is required. Therefore, it could be attractive to measure the target speed directly. This approach is the one to be discussed in this paper.

The low-cost ultrasonic tracking system under design has been earlier presented in [1]. This system consists of several time-multiplexed transmitters on the ceiling (see Fig. 1). The targets are small microphones attached to the human body. Each microphone receives and reads-out ultrasonic signals send by the transmitters. The 3-D positions are calculated using the Time-Difference-Of-Arrival (TDOA) method. The implementation of TDOA eliminates the effects of delays in the system and reduces the effect of changes in the sound speed, e.g. as produced by air turbulence and temperature changes [2].

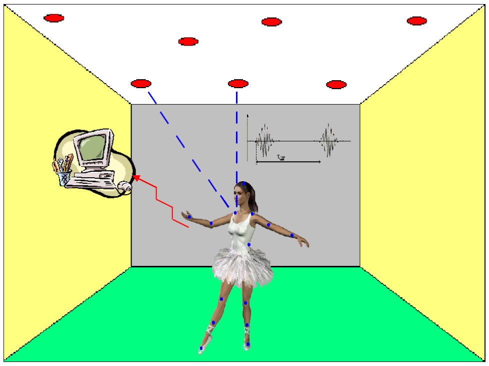

Figure 1. Ultrasonic Tracking System Overview

The system has been designed for sensing simultaneously a large number of tracking points, e.g. 50 targets or more. The update rate of each position does not depend on the total number of sensors. However, to track fast movements a high update rate will be required.

The speed-measurement system presented in this paper makes use of the Doppler effect, applying state-of-art pulse-wave (PW) ultrasound [4 - 6] techniques. In order to reduce the price and complexity of the system, it has been investigated how an optimal performance can be obtained, while reducing the sampling frequency, the number of data, and the observation time.

Section II introduces the system under consideration and the kind of signals available. In section III the principles of speed estimation based on the use of the Doppler effect in the relation to the observation time are introduced. To verify the analysis regarding the performance of the various methods an experimental setup has been realized. Section IV discusses the details of the hardware and software applied in this set-up. The practical results and an evaluation will be presented in section V.

II. 3-D ULTRASONIC TRACKING SYSTEM

The ultrasonic system under consideration consists of several transmitters (T_i, i= reference, 1, … , 6) on the ceiling, which are time multiplexed. Figure 2 shows the sequence of the ultrasonic signals coming from the transmitters. In this scheme, T_{slot} is defined as the interval time between two different emissions signals from the reference transmitter. T_{diff} stands for the time interval between the reference signal to each of the transmitters T_i, i=1, …,6.

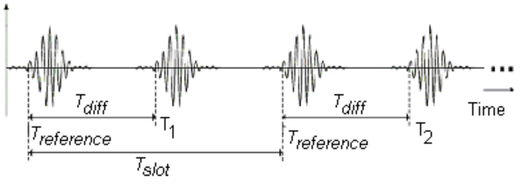

Figure 2. Sequence of the ultrasonic signals coming from the transmitters.

The targets are small microphones attached to the human body. Each microphone reads-out ultrasonic signals send by the transmitters. As an example, figure 3 shows the scheme of the ultrasonic signals at the location of a microphone. Depending on the distance with respect to the various transmitters, the acoustic signal will arrive at the microphone with a time T_{diff} plus a term $\Delta T_{r\text{-}i}$. The terms $\Delta T_{r\text{-}i}$, i =1, …,6, are equal to $\Delta T_{r\text{-}i} = (d_i - d_r)/c$, where d_r is the distance between the microphone to the reference transmitter, d_i is the distance between the microphone to each of the transmitter T_i (i=1, … , 6), and c is the speed of the sound.

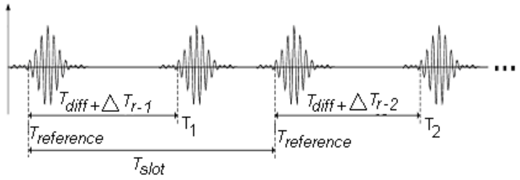

Figure 3. Scheme of the ultrasonic signals at the microphone

In this paper we will refer to the time intervals $T_{diff} + \Delta T_{r\text{-}i}$ as time-differences-of-arrival (TDOA). The terms $\Delta T_{r\text{-}i}$, i = 1, …,6, can be calculated as the difference between the TDOAs and the time T_{diff}.

The present study will focus onto the information available in each burst in order determine the instantaneous speed of the microphones. For a better understanding, figure 4 shows an ultrasonic burst obtained in one of our experiments. The crosses indicate sampling moments. The sampling frequency is f_s, the thicker line represents the envelope of the burst, and the other continues line is an approximation of the real acoustic signal. In the figure the peak value u_{peak} of the burst is indicated by an arrow. The observation time t_{ot} is a time interval with the acoustic peak value as centre.

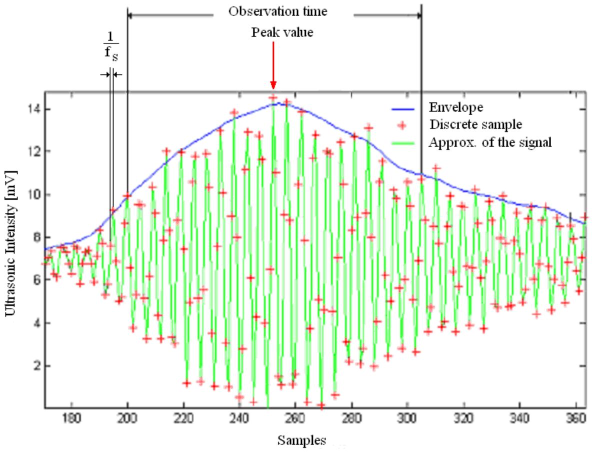

Figure 4. Ultrasonic burst received by the microphone

III. THEORY

A. Doppler principle

The Ultrasonic Doppler effect [3] results in a shift in the frequency and wavelength of the ultrasonic waves. This magnitude of the shift depends on the direction and magnitude of the motion of the microphone with respect to the transmitting ultrasonic source. The frequency will be higher if the ultrasonic source and the microphone approach each other. However, the frequency will be lower if they are separating. Thus, when a known frequency is sent out, estimation of the frequency shift is a direct speed measurement. The equation for the speed measurement based on Doppler effect is

$$\vec{v} = \frac{f_t - f_s}{f_t} \vec{c} \qquad (1)$$

where f_t is the transmitted frequency, f_s is the shift frequency, $\vec{v}$ is the velocity of the target, $\vec{c}$ represents the velocity of sound in air as a vector with the direction defined by a unitary vector from the transmitter to each microphone. Thus, velocity measurement based on Doppler effect is mainly a frequency estimation problem.

B. Frequency Estimation Techniques

When the sampling frequency is several times the Nyquist limit and the amount of data covers a few cycles of a periodical signal, most techniques for frequency estimation can give a similar result. However, when the amount of available data is restricted to a few samples, the sampling frequency is close to the Nyquist limit and the signal is quasi-periodical, then a good speed estimation is a big challenge. This holds also for the non-periodical ultrasonic signal shown in figure 4.

A historical perspective on frequency estimation problems is presented in [7 - 8]. There are 3 kinds of techniques for frequency estimation: (a) Classical techniques based on Fourier transform, (b) Parametric techniques based on rational transfer function models, and (c) Subspace methods.

A description of the details of these techniques is beyond the scope of this work. Instead of this, for methods based on the discrete Fourier transform, we will consider the most representative method for each kind as unwrapping angle [9] and zero padding [10]. Furthermore, the modified covariance (forward – backward) Burg method [11], multiple-signal classification (MUSIC) [12], and Estimation of signal parameters via rotational invariance technique (ESPRIT) [4] will be considered too.

C. Speed Estimation Overview for PW Ultrasound Mode

Frequency estimation techniques assume a periodical sine signal. However, the dynamic of human movements can rarely be characterized by a constant speed. Making the observation time t_{ot} so small that the signal can be assumed as to be a periodical sine wave can solve this problem (assuming that signal is a monocomponent). Thus, on one hand, the speed estimation will be more accurate when the observation time t_{ot} is short. On the other hand, depending on the applied technique, decreasing the observation time t_{ot} will deteriorate the resolution in speed estimation. A compromise between accuracy and resolution must be found.

Finally, the estimated speed is approximately equal to the average speed during the observation time. The accuracy of the speed estimation depends on the dynamic behavior of the human movement e.g. motion accelerations. In our study the applied observation time is in the range of 320 μs to 770 μs.

IV. EXPERIMENTAL SET-UP

A. Details of Software and Hardware Implementation

In our experimental set-up, with an Atmel microcontroller AT90S2313 in the transmitted module, the shape of the signal, the signal frequency, the initial phase, number of cycles, and time between the bursts can be modified. An electronic circuit amplifies the signal generated in the microcontroller and drives the voltage across the ultrasonic transducers of the type Polaroid 9000. When in our experiments a low signal-to-noise ratio was needed, only 5% of the total power of the ultrasonic transducer was used.

The microphones were of the type SQ-40-R of Quantelec. An acquisition board NI6014 of National Instrument has been used to read out the acoustic signal. The acquisition board has been controlled by a Matlab code. All the routines and codes for the signal processing have been running in Matlab (version 6.5 R13).

The frequency of transmission of the ultrasonic signal was 41.60 kHz. The sampling frequency at the receiver side ranges from 100 kHz to 200 kHz, with total amount of sampling data from 64 samples to 154 samples. The experiments have been performed for different Signal-to-Noise Ratios SNR. For each method and different conditions a thousand of measurements has been carried out. The data used for speed estimation are always surrounding the envelope peak. The peak can be estimated by using a low-pass filter, Hilbert transform or maximum-value detection (see fig. 4).

V. EXPERIMENTAL RESULTS

A. Instantaneous Speed Estimation for different SNR's

In ultrasonic acoustic systems the SNR is an important parameter. The SNR decreases by: (a) increasing the distance between transmitter and microphone; (b) increasing the misalignment between the microphone and transmitter. Therefore, it is important to study the performance of the different methods versus the SNR.

Figure 5 shows the standard deviation for different methods of speed estimation. The standard deviation refers to the value obtained after one thousand measurements under the same SNR conditions. For all the methods we used only 64 samples around the acoustic peak u_{peak} of the ultrasonic burst. The first method is the unwrapping angle, implemented as described in [9].

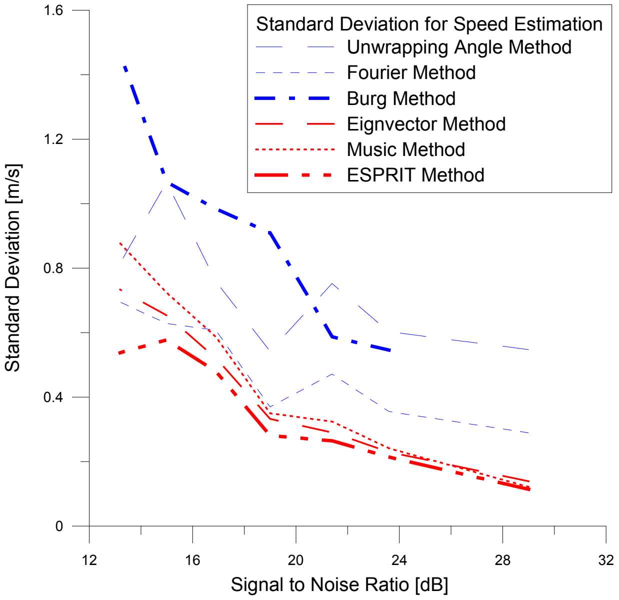

Figure 5. Standard deviation of speed estimation at different SNRs.

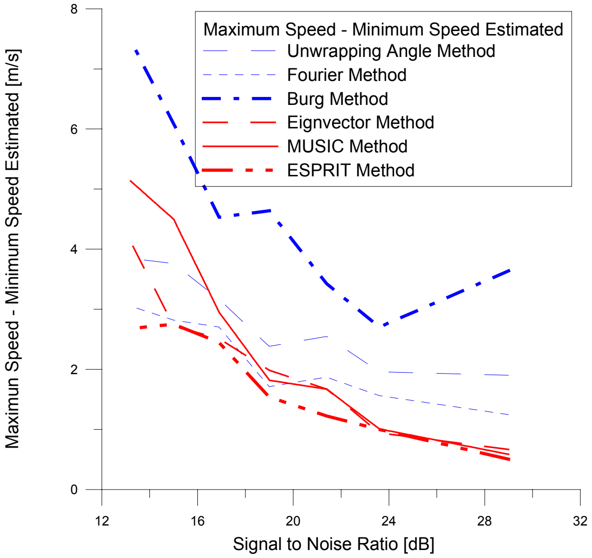

Figure 6. Maximum discrepancy of speed estimation different SNRs.

The second method is a Fourier method using 64 samples with zero padding [10]. Afterwards, using least square interpolation with a 2^{nd}-order equation, the Power Spectrum Density that surround the peak has been fitted and the maximum representative frequency has been obtained. With formula (1) the frequency resolution is converted to a corresponding speed value.

The other four methods are the Burg method the Eigenvector method, the MUSIC method and the ESPRIT method [11], respectively.

From figure 5 we can conclude that the Eigenvector method, the Music method and the ESPRIT method give the best speed estimation for different SNRs. At low SNR the ESPRIT method shows the best performance.

Figure 6 shows the maximum speed error as found from a set of thousand measurements. This maximum speed error has been computed as the maximum estimated speed minus the minimum one. For the unwrapping angle method, the Fourier method and the Burg method the maximum speed errors are larger than 1 m/s, even at the highest SNR. Based on this observation we decided to focus this study upon the use of the Eigenvector method, the MUSIC method and the ESPRIT method, while the Burg method is kept as a reference for the worst-case method.

B. *Instantaneous Speed Estimation for Different Numbers of Samples*

The observation period depends on the total number of samples and the sampling frequency (see figure 4). As mentioned before, the use of a short observation time will give a better estimation of the instantaneous speed. However, shortening the observation time will also decrease the resolution of the speed estimation.

Figure 7 shows the behavior of the Eigenvector method, the MUSIC method and the SPRIT method for different numbers of samples. For all the cases, we used the data surrounding the peak in the ultrasonic burst. For each case a thousand measurements have been carried out. We can conclude that when the amount of data has been increased from 64 samples to 154 samples, for the Eigenvector, the MUSIC method and the ESPRIT method the standard deviation will be reduced with about a factor 3. The best speed estimation has been obtained with the ESPRIT method. For this method the standard deviation was 0.1 m/s and 0.033 m/s for 64 and 154 samples, respectively. For each method the maximum error in the speed estimation is shown in figure 8. For the ESPRIT method the maximum speed error computed as the maximum estimated speed minus the minimum one were 0.6 m/s and 0.19 m/s for 64 samples and 154 samples, respectively.

C. *Instantaneous Speed Estimation for different sampling frequency*

When for certain reasons the available data for frequency estimation is limited, increase the sampling frequency is not a good option. Increase the sampling frequency would reduce the observation time, which would make the instantaneous speed estimation noisier.

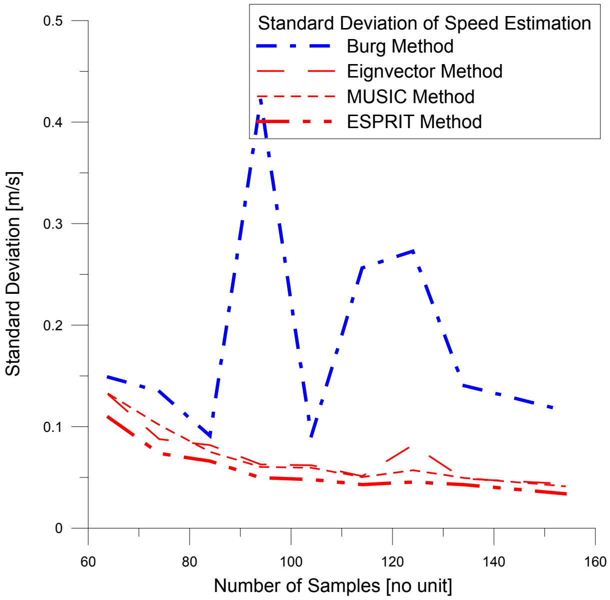

Figure 7. Standard deviation of speed estimation for different number of samples.

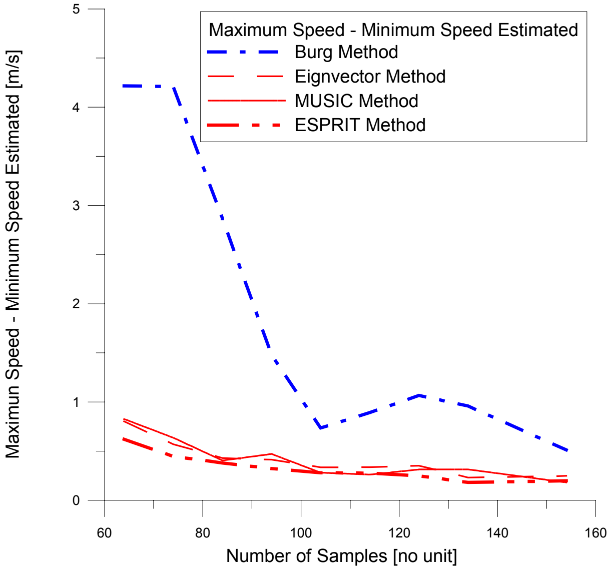

Figure 8. Maximum discrepancy of speed estimation for different numbers of samples.

To overcome this problem, both the sampling frequency and the frequency of the transmitted acoustic signal can be increased. However, in most practical implementation, the transmitted frequency is selected according to other important criteria e.g. the maximum tracking distance of the system and the required resolution.

Figure 9 shows the behavior of speed estimation for each method at different sampling frequencies for a fix SNR of about 19 dB. The amounts of samples used were 64 samples.

As mentioned before, improvement in standard deviation of the speed estimation is possible by reducing the sampling frequency. However, this will yield a longer observation time.

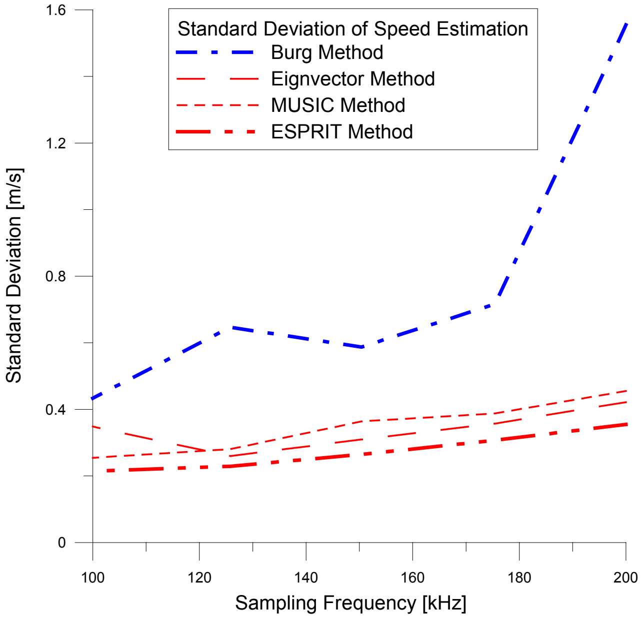

Figure 9. Standard deviation of the speed estimation versus the sampling frequency.

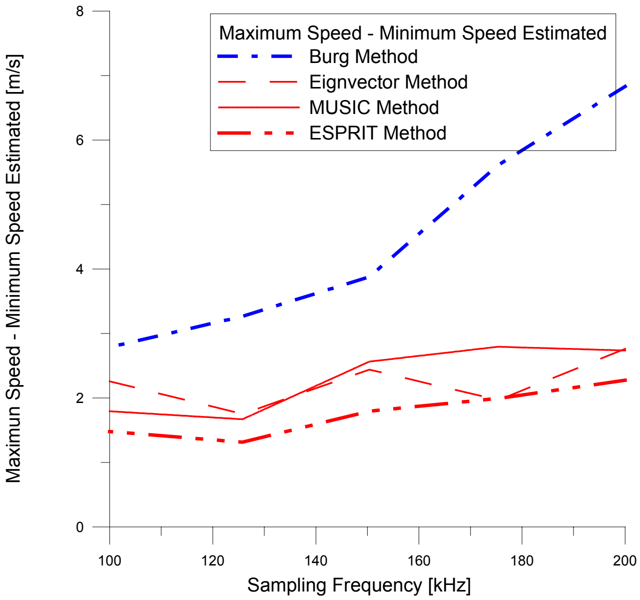

Figure 10. Maximum discrepancy of speed estimation versus the sampling frequency.

When the sampling frequency is reduced from 200 kHz to 100kHz with the ESPRIT method the standard deviation decreases from 0.35 m/s to 0.21 m/s. The maximum error in the speed estimation was about 2.3m/s at a sampling frequency of about 200 kHz and decreases to about 1.5 m/s at sampling frequency of about 100 kHz.

The minimum discrepancy in speed estimation is found around 120 kHz. It can be concluded that when using the ESPRIT method the optimum sampling frequency is about three times the transmitted frequency of the ultrasonic signal.

VI. CONCLUSIONS

Using the pulse-wave Doppler effect it is possible to realize a direct speed-measurement system with a short observation time.

Several speed-estimation methods have been considered. For the different methods and for different conditions, the resolution has experimentally been investigated. For each method and for each condition, to find the statistical values a thousand measurement has been carried out.

The ESPRIT method shows the best resolution. Using 64 samples the standard deviation for speed estimation was from 0.5 m/s at a SNR about 13 dB and 0.11 m/s at a SNR of about 29 dB, respectively. The resolution in the speed estimation improves when the observation time increases. However, a longer observation time will decrease the data rate. When using 154 samples, an observation time of 770 μs and an SNR of about 30 dB the resolution reduces to only 0.03 m/s. However, for an SNR of about 12 dB this best result will deteriorate with about a factor 5.

For a fixed amount of data, a reduction of the sampling frequency will also improve the standard deviation of the speed estimation. For the ESPRIT method the optimal sampling frequency is about three times the frequency of the transmitted signal.

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