A 24-GHz Tank Level Gauging System with State-Space Frequency Estimation and a Novel Adaptive Model Order Selection Algorithm

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Abstract — **For the evaluation of signals in frequency modulated continuous wave radar systems for object distance measurement tasks, highly sophisticated state-space frequency estimation algorithms pose an alternative to the traditionally used fast Fourier transformation. Current implementations of this approach suffer from instability problems when applied to real radar measurements. In this paper a method is presented to overcome the present stability problems by proposing a novel model order estimation procedure. With the use of practical measurements in a level gauging system an improvement of 2-3 over the resolution of the FFT-based methods is shown, and stability of the model order selection algorithm is proved.**

I. Introduction

Radar systems have become the tool of choice for tank-level gauging over the last few years. They offer robustness to harsh environmental conditions, precision in the mm-range and competitive pricing. Among the current systems FMCW radars operating at 24 GHz achieve excellent accuracy, high resolution, and offer compact antenna sizes. Furthermore novel production techniques for RF-frontends significantly lowered the overall system cost [5], [6].

Multi-target capability is an important asset of radar systems. Usually industrial tanks contain additional reflectors other than the filling level, e.g. a stirring apparatus or the tank bottom. When the liquid level is close to the additional reflectors, fine range resolution is necessary to avoid severe distortions of the measurement results. Unfortunately the resolution of radar systems is limited by the bandwidth and the applied signal processing strategy. Since the available bandwidth is limited by either regulatory or technical means, application of appropriate signal processing algorithms needs special attention. Therefore, the system presented in this paper uses state-space algorithms to increase the resolution by a factor of two to three.

The main goal of this paper is the implementation and modification of existing state-space algorithms to meet the requirements of real radar systems. A novel approach for one of the key problems of state space algorithms, the model order estimation, is presented and verified with actual measurements in an industrial tank.

II. FMCW Signal Model

FMCW radar systems essentially measure the channel frequency response by transmitting a highly linear frequency sweep, or chirp, ranging over some bandwidth B, and mixing the transmit signal with received reflections coming from objects in the antenna beam. For ideal point-targets, the Radar output signal prepared for digital signal processing by A/D-conversion then is a superposition of – possibly complex – sinusoids of different digital frequencies ω_k that are proportional to object distances,

$$y_n = \sum_{k=1}^{p} c_k e^{i\omega_k n} \qquad n = 0,\dots,N-1. \qquad (1)$$

This property directly indicates that multiple targets can be detected and positioned simultaneously.

III. Fast Fourier Transformation

With (1), the problem of distance estimation using FMCW radar systems reduces to that of frequency estimation of a sampled, finite-length time-domain set of measurement data. Most commonly used for solving the problem at hand is a Fast Fourier Transformation of the data sufficiently extended with zeros to give an estimate of the signal's amplitude density spectrum. The major advantages of FFT-based systems are the inherent stability of this approach, and the widespread availability of implementations. The frequency components contained in the signal are resolved as different peaks, and their locations along the frequency axis can be used as fairly accurate estimates for the desired signal frequencies. From the theory of the Fourier Transformation one knows that time-windowing a sinusoidal signal results in spectral convolution of the spectrum of the window function with the infinitely narrow Dirac-functions in the amplitude density

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spectrum of an ideal sinusoid. The result is a widening of the peaks in frequency domain that leads to interference between signal components and consequently – depending on window function, frequency spacing, initial phases and amplitudes – errors in frequency estimates or even the inability to resolve signals closely spaced in frequency.

IV. State-Space Frequency Estimation

Several other methods for frequency estimation exist, e.g. the well-known state-space method [1] that is based in the time-domain and consequently avoids any problems arising from time-limitation. The algorithm is based on a state-space model of a discrete-time linear oscillator generating N samples of the radar output signal y_n,

$$\begin{aligned} \mathbf{x}_{n+1} &= \mathbf{A}\mathbf{x}_n \qquad n = 0,\ldots,N-1 \\ y_n &= \mathbf{c}^T\mathbf{x}_n. \end{aligned} \tag{2}$$

If a portion of M (selected e.g. as $N/2$) individual measured data samples are written in vector notation, i.e.

$$\mathbf{y}_n = \begin{bmatrix} y_n & y_{n+1} & \cdots & y_{n+M-1} \end{bmatrix}^T, \tag{3}$$

matrix model parameters $\mathbf{A}$ and $\mathbf{c}$ can be derived from a singular value decomposition of the data covariance matrix defined as

$$\mathbf{R}_{yy} = E\{\mathbf{y}_n\mathbf{y}_n^*\} \tag{4}$$

as described in [1]. The desired frequency estimates are then contained in the complex angles of the eigenvalues of the state feedback matrix $\mathbf{A}$. With this state-space algorithm, a given number of estimates are computed directly, i.e. without the necessity of performing a peak-search, with further advantages of high accuracy and resolution. Amplitudes can be estimated in a second step involving calculation of a simple linear least-squares fit of the data model to the measured samples.

V. Model Order Estimation

One of the most challenging problems in the evaluation process is that of selecting a model order p, i.e. the dimension of the square state feedback matrix $\mathbf{A}$ and simultaneously the number of sinusoidal components in the signal y_n, that is appropriate for the specific radar measurement. The nature of the radar signal originating from sounding a radar channel containing a multitude of objects and reflections implies presence of a high number of sinusoids of different frequencies in the signal y_n, most of which are not of interest. The exclusion of such reflections in the process is crucial to the plausibility of distance estimates as well as to correct operation of the frequency estimation algorithm itself. Selecting the model order too low necessarily results in loss of signal components, and possibly frequency estimation error, choosing p too high may result in spurious peaks of high amplitude obscuring the actual signal peaks, or in ill-conditioning of the state-space matrix.

One possibility to obtain a model order estimate is to look at the so-called singular value spectrum of the data covariance matrix, i.e. its singular values arranged in decreasing order. Ideally, a notable gap in magnitude appears after the first p singular values, providing a possible estimator. The magnitude of this gap depends strongly on signal parameters and generally decreases with increasing number of signals. Consequently the reliability of this estimator is usually not sufficient. Furthermore, smearing of the components is caused by systematic distortions.

Other statistical criteria like the Akaike Information Criterion (AIC) [2] fail to account for the typical systematic distortions present in radar signals. Consequently their performance is poor with real technical signals [7].

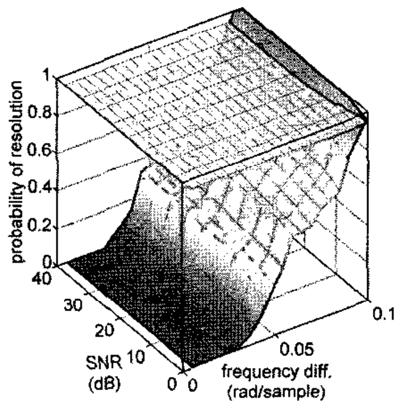
A completely different approach is taken in an adaptive model order estimation procedure. It is based on the idea that the unwanted effects seen in evaluation results with p set too high can be utilized to detect the model order. Starting at a fairly high value of p – possibly derived from the last value in a series of measurements – the final frequency and amplitude estimates obtained from application of the state-space frequency estimator are searched for one or more of the following effects:

- complex frequencies
- frequencies spaced too closely
- frequencies close to zero or half the sampling rate
- amplitudes below the noise floor

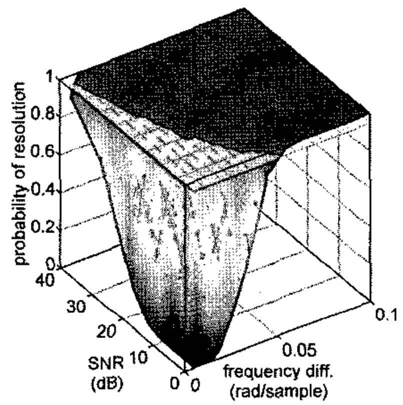
If any of these is encountered, the model order is decreased by one or two, for complex- or real-valued measurements, respectively. The procedure is repeated until a stable model order estimate without any spurious frequency components is reached.

V. Simulation Results

The stated improvement in resolution that the state-space approach permits is verified via a statistical simulation of two discrete sinusoids of length $N = 128$ in additive, white, Gaussian noise that was repeated 100 times for different combinations of frequency spacing and SNR, which is defined here with respect to one of the two sinusoids. Clearly visible in Fig. 2 is the superiority of the state-space approach over the FFT. While the latter reliably resolves the two signals first at a frequency difference

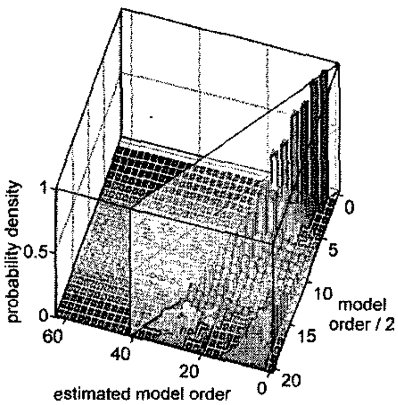


(a)

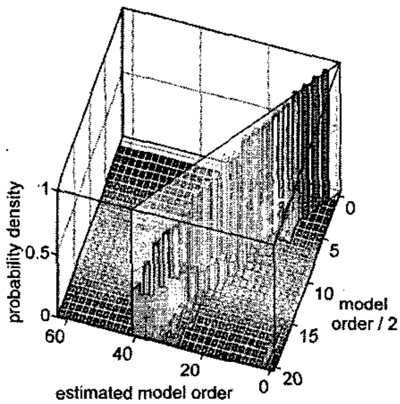


(b)

Fig. 2. Probability of resolving two equi-amplitude sinusoids in additive, white noise over frequency difference and SNR with respect to one sinusoid for (a) FFT and (b) state-space frequency estimation.



(a)



(b)

Fig. 1. Frequency of occurrence of the estimated versus the true model order of a synthetic signal consisting of model order / 2 real-valued sinusoids for (a) the singular value spectrum model order estimator and (b) the adaptive procedure.

of 0.1 rad/sample which corresponds roughly to twice the FFT grid spacing without zero-padding of $\frac{2\pi}{N}$, the state-space algorithm shows high probability of resolution at much lower frequency differences, with performance increasing with SNR.

For evaluation of the adaptive model order estimator, simulations were performed using synthetic FMCW radar output signals consisting of a sum of 2 to 40 equi-amplitude, real-valued sinusoids. Again, experiments were repeated 100 times for each model order to facilitate statistical evaluation. The resulting histograms of the estimated model order are depicted in Fig. 1 (a) and (b) for the singular value spectrum estimator and the adaptive procedure, respectively. Clearly, the singular value spectrum as an indicator for the model order fails to work except for a very low number of sinusoids; for higher orders the estimates tend to be much too low. The adaptive algorithm, in contrast, most likely yields the correct, or at least a model order close to the correct value up to a large number of sinusoids.

As a realistic test case for an FMCW tank level gauging radar a scenario with 8 unevenly spaced reflectors of different magnitude with an SNR of 20 dB with respect to the largest reflection was simulated for an FMCW signal at 24 GHz with a bandwidth of 200 and 600 MHz, respectively. Fig. 3 that shows the FFT spectra and the combined frequency/amplitude estimates of the state-space algorithm illustrates the increase in resolution achieved with the state-space approach, that is comparable to tripling the bandwidth in FFT evaluation.

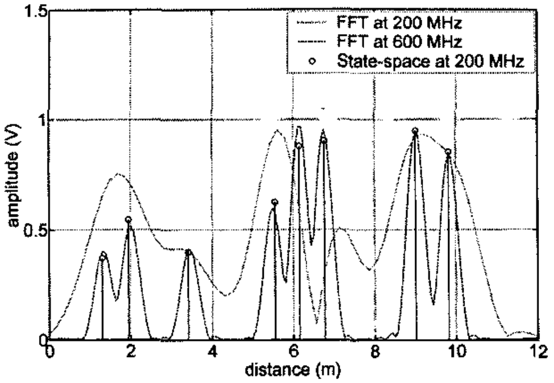


Fig. 3. Evaluation of a simulated multi-target scenario with the FFT at 200 and 600 MHz bandwidth, and with the state-space algorithm at 200 MHz.

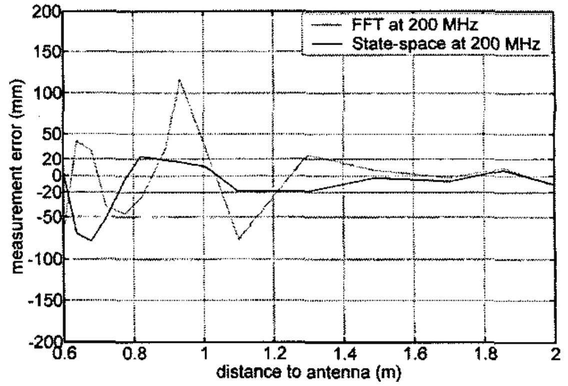


Fig. 5. Measurement error achieved in estimation of the liquid level distance from the antenna during filling of the tank.

VI. 24-GHz Tank-level Measurement

The algorithms described were tested in a real-world FMCW radar setup in a 24-GHz tank-level gauging system that is schematically shown in Fig. 4. A traverse in the tank and possible multiple echoes between liquid and the tank surface are sources of error for the liquid level determination. A bandwidth of 200 MHz, which is within the allowed range in the 24-GHz ISM-band, was used for taking several measurements during the filling of the tank. The difference of evaluation results from the FFT and the state-space algorithm to the known true filling level is shown in Fig. 5. Clearly, the state-space approach yields accurate results within ±20 mm down to a distance of about 0.8 m to the antenna, while the FFT result suffers from disturbance by unresolved reflectors and thus stays in this range only down to approximately 1.2 m.

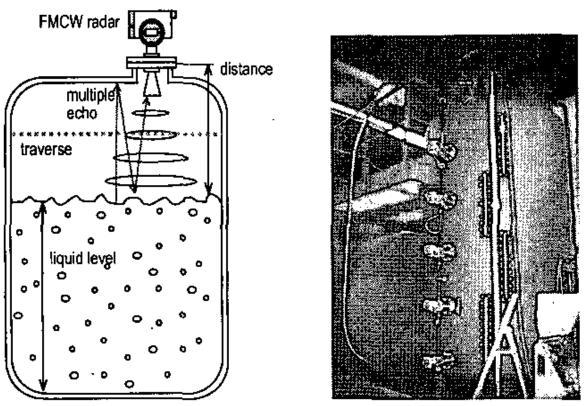


Fig. 4. 24-GHz tank-level measurement setup and photograph.

VII. Conclusion

A state-space frequency estimation algorithm was shown to outperform the FFT-based estimator with respect to accuracy and resolution in a tank-level gauging system. Stability problems that are a topic in current implementations of the state-space approach were overcome by a novel model order selection algorithm.

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