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Research Article

Detection of Overhead Contact Lines with a 2D-Digital-Beamforming Radar System for Automatic Guidance of Trolley Trucks

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The benefit of trolley truck systems is the substitution of the diesel fuel by the cheaper and more ecological electrical energy. Trolley trucks are powered by electricity from two overhead contact lines, where one is the supply and the other the return conductor. Such trolley trucks are used for haulage at open pit mining sites but could also be used for freight traffic at roadways in the future. Automatic guidance prevents the trolley-powered trucks from leaving the track and thus allows higher operating speeds, higher loading capacity, and greater efficiency. Radar is the ideal sensing technique for automatic guidance in such environments. The presented radar system with two-dimensional digital beamforming capability offers a compact measurement solution as it can be installed on top of the truck. Besides the distance measurement, this radar system allows to detect the location and inclination of the overhead contact lines by digital beamforming in two dimensions. Besides automatic guidance, the knowledge of the inclination of the overhead contact lines could allow automatic speed adaption, which would help to achieve maximum speed especially in hilly terrain.

1. Introduction

The benefit of trolley truck systems is the substitution of the diesel fuel by the cheaper and more ecological electrical energy [1]. Trolley trucks are powered by electricity from two overhead contact lines, where one is the supply and the other the return conductor. Such vehicles are often used for haulage at open pit mining sites in order to save fuel and increase productivity [2, 3]. Recently, Siemens AG started the eHighway project [4] for electrification of freight traffic. The system can be installed with only limited alterations to current roadways. These diesel-hybrid driven trucks would help to cut the fossil fuel use and reduce pollution in residential and agricultural areas. Adding an automatic guidance feature to trolley trucks would help to keep the truck on track under the overhead contact lines. Thus, it would provide an increased driving safety and therefore it could allow for higher loading capacities and higher operating speeds. Besides automatic guidance, the knowledge about the inclination of the overhead contact lines allows automatic speed adaption, which would help to achieve maximum speed especially in hilly terrain.

Due to its day and night operability and robustness in harsh environments, radar is the ideal sensing technique for such an application.

In this proposed guidance solution, radar is used to detect the location and inclination of overhead contact lines. Compared to other existing guidance systems described in [5], neither fixed installations in the surrounding area nor changes on the current collectors are required, as the radar system can be installed on top of the truck as shown in Figure 1. Besides the distance measurement of the overhead lines, the presented radar system [6] provides angular information in two dimensions by applying digital beamforming (DBF) [7].

In the first part, a short overview of the realized radar system and its characteristic features is given. The measurement setup and signal processing aspects for the detection of

Table 1: Settings of the system parameters.

Frequency f_0	Bandwidth B	Sweep duration T_S	Measurement cycle T_c	Sampling frequency f_a
24 GHz	270 MHz	2.5 ms	20 ms	250 kHz

Table 2: Parameters of the two different measurement setups.

Setup	Contact line	Height [m] h_1	Height [m] h_2	Antenna height [m] e	Distance [m] d	Length [m] l	Angle [°] α
1	1/2	3	3	0.38	0.6	1.9	0
2	1/2	3	2.5	0.38	0.6	1.9	15.3

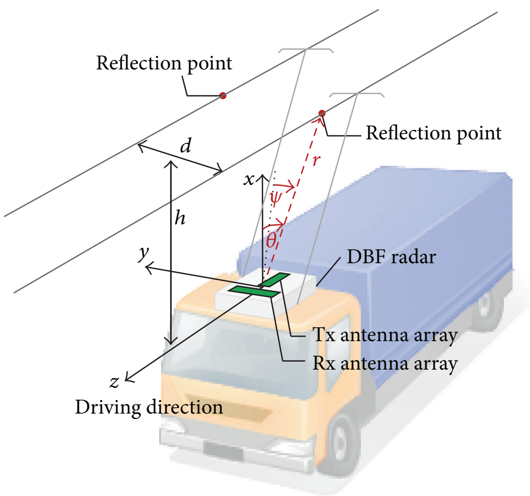


Figure 1: Drawing of the trolley truck with 2D-DBF radar on top.

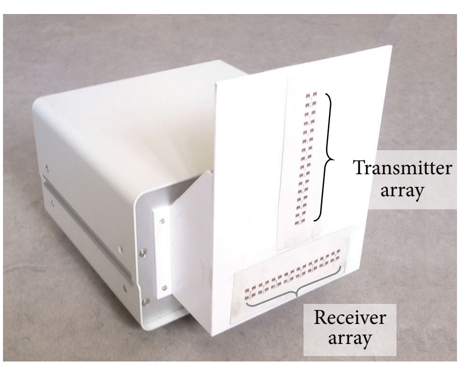


Figure 2: Realized 2D-DBF radar system with orthogonally arranged transmit and receive antenna arrays.

overhead contact lines are treated afterwards. In the final part, measurement results of two metal bars verify the applicability of the proposed sensing technique.

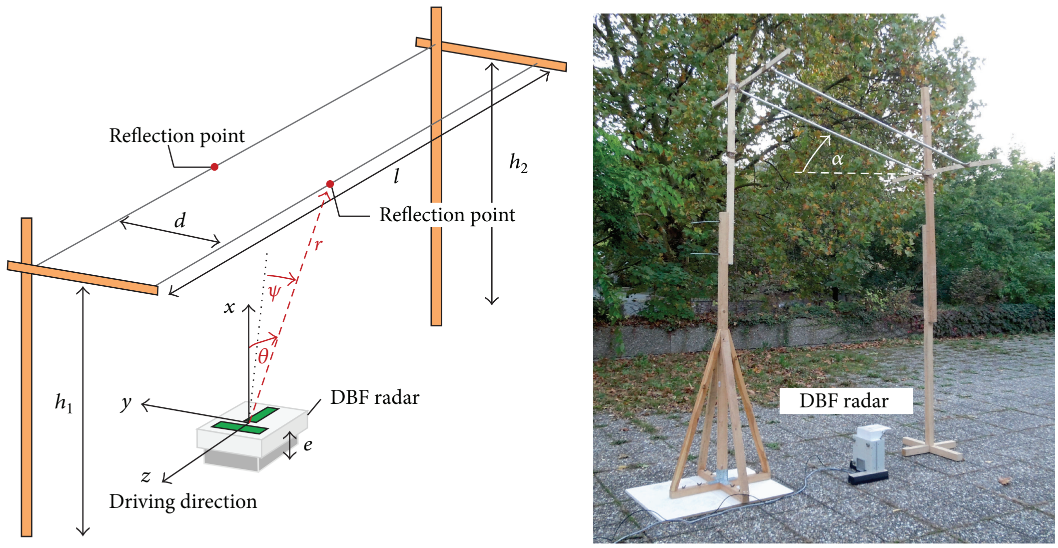
2. DBF Radar System

The realized DBF radar system is a 24 GHz frequency modulated continuous wave (FMCW) radar system with a sweep bandwidth of 270 MHz. It comprises eight transmitter and eight receiver channels [6]. As shown in Figure 2, the transmitter and receiver antenna arrays are arranged orthogonally to each other in the form of an inverted T. This arrangement of the antenna arrays enables to measure the angles, denoted by θ and ψ, of the reflected signals in two dimensions by DBF. For the transmitter and the receiver antenna array, the same design consisting of four vertical polarized subpatches per antenna element is used in the same orientation. The single patch antenna provides a half-power beamwidth (HPBW) of 42° in azimuth and 50° in elevation. The HPBW of the transmitter array in elevation is determined by measurement to 5.8° and the HPBW of the receiver array in azimuth to 6°, respectively. Besides the distance provided by the FMCW measurement principle, the location and inclination of the two overhead contact lines can be determined by DBF. Since the radar is laid down (Figure 1), the radar's elevation is now equal to θ and its azimuth to ψ, respectively. The DBF radar system is realized on several modules for which a detailed description can be found in [6, 8]. DBF on transmit is performed by time-division multiplexing with eight independently switchable transmitters, whereas eight receiver channels allow simultaneous acquisition and processing of the radar signal. A measurement cycle in which the transmit signal is switched from transmit antenna one to eight takes 20 ms. In Table 1 the system parameter settings of the radar system are given.

3. Measurement Setup

For demonstration of the presented 2D-DBF radar system and its suitability for detection of overhead contact lines, a measurement setup with two metal bars with a diameter of 2 cm is chosen. As shown in Figures 3(a) and 3(b), the two metal bars are mounted in parallel with a distance d and a height h above the radar system. The 2D-DBF radar system is oriented on the floor with the transmit antenna array along the driving direction (z-axis) and the receiver array orthogonal to it (y-axis). The angular positions of the overhead contact lines in y-direction can be determined by DBF on receive, whereas the inclination of the overhead contact lines is obtained by DBF on transmit.

Two different measurement setups are investigated with the parameters given in Table 2. The first measurement setup with two parallel overhead contact lines, both mounted in the same height, represents the usual case and is shown



(a) Drawing of setup 1

(b) Photograph of setup 2

Figure 3: Setup for measurement of the overhead contact lines with the 2D-DBF radar system.

Table 3: Comparison of theoretical and measured ranges and angles.

Setup	Contact line	Theoretical range [m]	Measured range [m]	Theoretical angle [°]		Measured angle [°]	
		r	r	ψ	θ	ψ	θ
1	1	2.64	2.66	6.5	0	+6.1	0
	2	2.64	2.66	−6.5	0	−6.1	0
2	1	2.39	2.36	7.2	15.3	+7.5	15.4
	2	2.39	2.36	−7.2	15.3	−7.5	15.4

in Figure 3(a). The photograph in Figure 3(b) shows the measurement setup 2, in which the two metal bars are hung up with an inclination of $\alpha = 15.3^\circ$.

4. Signal Processing

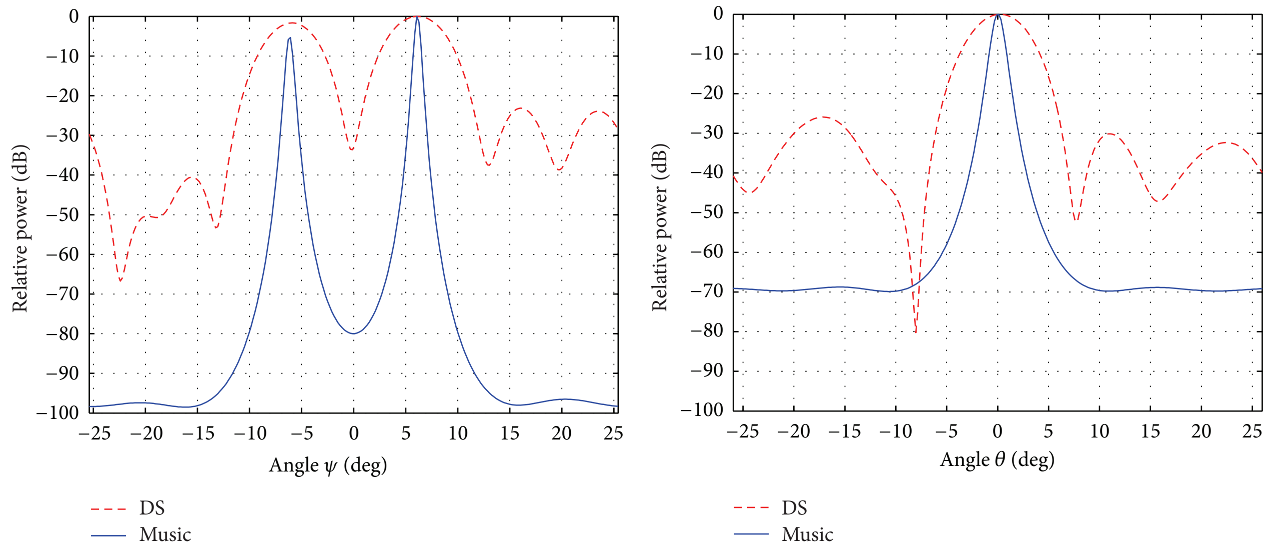
The distance from the radar system to the overhead contact lines is obtained by the FMCW principle. The location and inclination of the two metal bars are determined by digital beamforming in two dimensions [6]. For angular processing of the measured data the conventional delay-and-sum (DS) beamformer based on the fast fourier transform and the multiple signal classification method (MUSIC) are used. MUSIC is the so-called super resolution technique and was firstly introduced in [9]. Range and azimuth processing can be directly started after one FMCW sweep as the reflected signal of one transmitter is measured by all receiver channels simultaneously. After one complete transmit cycle, in which the transmitters are switched successively, digital beamforming on transmit can be performed in order to determine the inclination of the metal bars.

5. Measurement Results

After range processing of the measured data, 2D-DBF is applied onto the range cell in which the overhead contact lines are located. The angular spectra for measurement setup 1 are shown in Figures 4(a) and 4(b), respectively. The two overhead contact lines can be discriminated in the angular spectrum lateral to the driving direction, and their locations are measured to $\psi = \pm 6.1^\circ$. In Table 3 the measured ranges and angles are given in comparison to the theoretical values, which are calculated from the parameters of the measurement setups in Table 2. As the overhead contact lines are mounted horizontally above the floor, the peak in the angular spectrum along the driving direction is located at $\theta = 0^\circ$. In the second configuration the overhead contact lines are mounted with an inclination of $\theta = 15.3^\circ$, which is determined to $\theta = 15.4^\circ$ by the radar in Figure 5(b).

Due to the inclination, the two metal bars have a shorter distance to the radar system. Thus, the angles acquired by DBF on receive increase to $\psi = \pm 7.5^\circ$ (Figure 5(a)) compared to measurement setup 1 (Figure 4(a)). The slight deviations in the presented measurement results can be explained due to the nonideal measurement setup and inaccurate placement of the DBF radar system under the overhead contact lines.

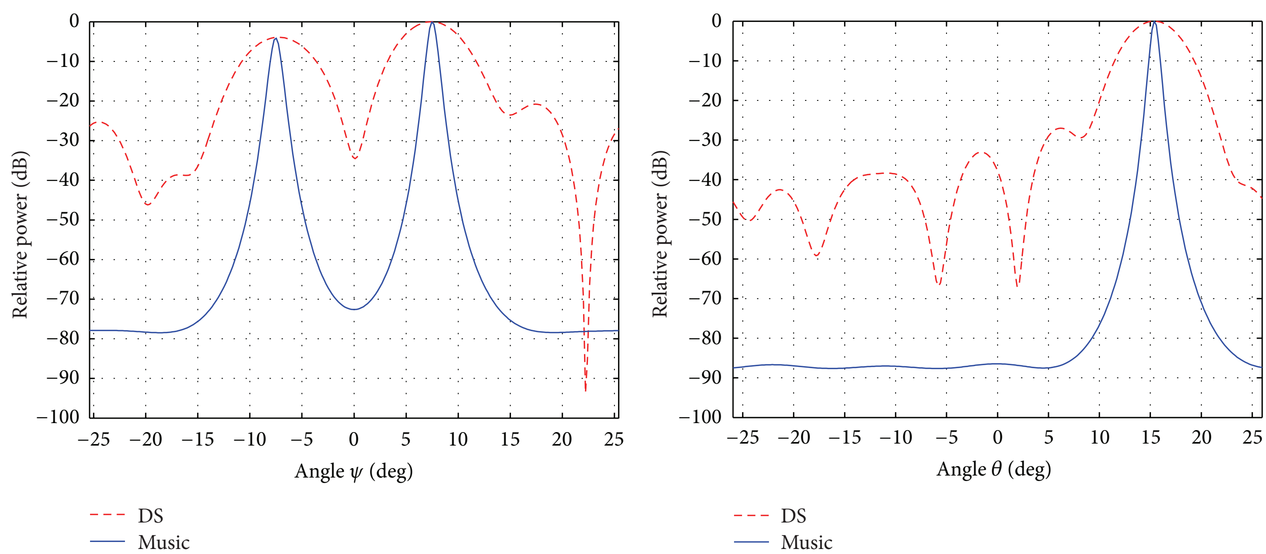
Comparing the two angular processing methods, broader peaks and higher side lobes can be observed for the DS. In some situations it can be more difficult to detect the overhead contact lines by using DS. On the other hand, applying MUSIC presupposes knowledge of the exact number of targets. In real-world environments, where more objects beside



(a) Angular spectrum lateral to driving direction

(b) Angular spectrum along driving direction

Figure 4: Measurement results of setup 1.



(a) Angular spectrum lateral to driving direction

(b) Angular spectrum along driving direction

Figure 5: Measurement results of setup 2.

the two overhead lines may be existing, additional estimating techniques could be required [10, 11]. Even further signal processing as, for example, tracking of the overhead contact lines or range gating could be implemented to discriminate the overhead contact lines from other targets [12].

6. Conclusion

In this paper a radar-based measurement technique for the detection of overhead contact lines of electrically powered trolley vehicles is presented. It is shown by measurements of two metal bars that the realized DBF radar system allows one to detect their location lateral to the driving direction as well as their inclinations. Two different spectrum estimation methods are applied and compared for angular processing of the measured data, and the same angular values are obtained with both. The proposed DBF radar offers an ideal measurement system which can be used for automatic guidance and automatic speed control of trolley vehicles. Further, it offers a robust and compact solution particularly for open pit mining sites as no further installations are required.

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