An Experimental Study on Using Electronically Scanning Microwave Radar Systems on Surface Mining Machines

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***Abstract*— Using a series-model of an automotive short range radar sensor (SRR) and a recently completed experimental radar system, field tests have been performed in a surface mine. It was examined, to what extent low-cost electronically scanning radar sensors can provide useful data for assistance systems in large scale mining machines. The series SRR sensor using mono-pulse principles for cross range measurement, proved to be useful to supervise the safety zone of a bucket wheel excavator. The more complex and sophisticated experimental radar system using digital beam-forming for cross range processing, can clearly detect and map the contours of trenches and escarpments. The overall promising results refer to many more potential applications for electronically scanning radar in surface mining and motivate to adapt the experimental sensor for such applications.**

***Index Terms*—Electronically scanning radar, digital beam-forming, surface mining applications.**

I. Introduction

Assistance systems for the operators of large scale surface mining machines help to increase effectiveness and to increase safety. The basic principle of such a system is that a machine can collect the particular information faster and more accurate as a human [1]. The core data of these assistance systems is real time geometrical information of machine components, obstacles or slopes. However, the surroundings of mining machines are changing permanently and the shapes of objects to be observed are typically complex and random. Today, this information is not available, as optical imaging systems (laser scanner, camera systems) are suffering largely by dust and vapour. In comparison to optical sensor systems, radar is able to penetrate dust and fog and is less sensitive to dirt on the sensor [2]. The advantages of radar systems will only be decisive, if sufficient angular resolution for the intended applications can be achieved for acceptable cost. Extreme environmental conditions, mechanical stress and vibrations make the realization of reliable and maintenance-free mechanical scanners very complex and expensive. Electronically scanning radar can address these problems appropriately. The consecutive reported results of field tests performed with two different electronically scanning automotive radar sensors in a coal mine emphasizes this statement.

II. Applied Sensors

A. SLR-Automotive Sensor

The sequential lobing radar (SLR) sensor (Fig. 1) was developed by Tyco Eletronics M/A-COM and is available for the Mercedes S-Class since 2005 [3]. The development goal was a simple architecture to achieve a low cost sensor for mass application. In the automotive application several sensors of this type are installed in the front- and the rear-bumper. Cross range information can be obtained by using two switchable RX antennas and one TX antenna through signal processing based on the monopulse principle. Ten objects can be tracked with an object range resolution of 15cm. However due to the used principle, objects in the same range but at different angles may cause detection instabilities. The sensor can detect moving and non-moving objects and provides the range, bearing, velocity and normalized amplitude information via a CAN-bus interface. The access to the raw data is not possible. The minimum range is 5cm, the maximum range is 30m for a target with a cross section of 10dBsm in forward direction.

Fig. 1. Photograph of the SLR-Automotive Sensor.

Fig. 2. Photograph of the HARFE Experimental System with the front-end (top) and the radar electronics (bottom).

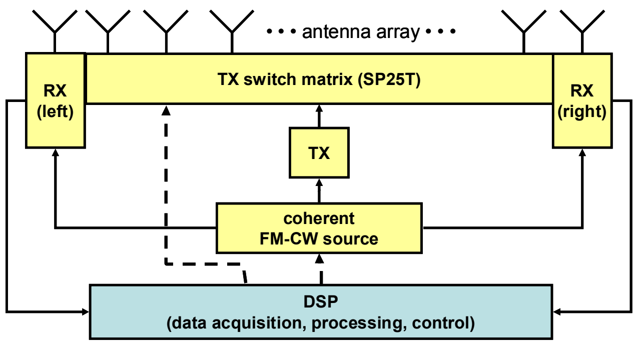

Fig. 3. Simplified block diagram of the HARFE experimental system.

B. *HARFE Experimental System*

The HARFE system (Fig. 2) is an experimental radar which was realized in a cooperation between the Ulm University and DaimlerChrysler [4,5]. The goal of the related research project was the transfer of the advantages of state of the art high-end electronically scanning radar systems to a low-cost automotive sensor architecture. The front-end combines a switched array of 25 linearly arranged transmit antenna elements and a two channel homodyne FM-CW architecture (Fig. 3). The two receivers left and right to the transmit array are working in parallel. A coherent FM-CW source is providing the transmit signal and the local oscillator signals for the receivers. In a measurement sequence one-dimensional FM-CW radar scans are successively performed and stored for all the transmit elements. The resultant 50 radar scans in time domain are synthesized to a two-dimensional radar image in a two step signal processing process. In the first step normal range processing using the fast Fourier transform (FFT) is applied to each response resulting in 50 range responses. In the second step, cross range processing is performed for each range cell regarding the 50 element combinations as a synthetic aperture. The open architecture and the completely coherent operation allow using various methods of digital beam-forming for cross range processing. Some of them will be discussed in paragraph IV.

III. Measurements on a Bucket Wheel Excavator

The anti-collision sensor test was conducted on a large bucket wheel excavator in an open pit lignite mine of RWE Power between Aachen and Cologne in Germany. Recent advances in microwave radar technology are giving new impulses to develop robust automation and control systems for huge mining equipment. The boom of the bucket wheel excavator has a length of 95m, the bucket wheel has a diameter of about 15m (Fig. 4). Thus the operator has a very restricted view on the machine, which can be further reduced by dust and fog. The concept is to determine the ground line and obstacles in the protection zone besides the bucket wheel. For the tests an individual temporary frequency assignment has been issued by the German federal network agency.

The SLR Radar was installed about 11m above ground. To overcome the problems of the SLR with several objects at the same range, the sensor is inclined with 40° to the ground so that the ground will appear as a set of objects in different range and angle. Additionally the installation position is chosen to avoid mechanical damage of the sensor.

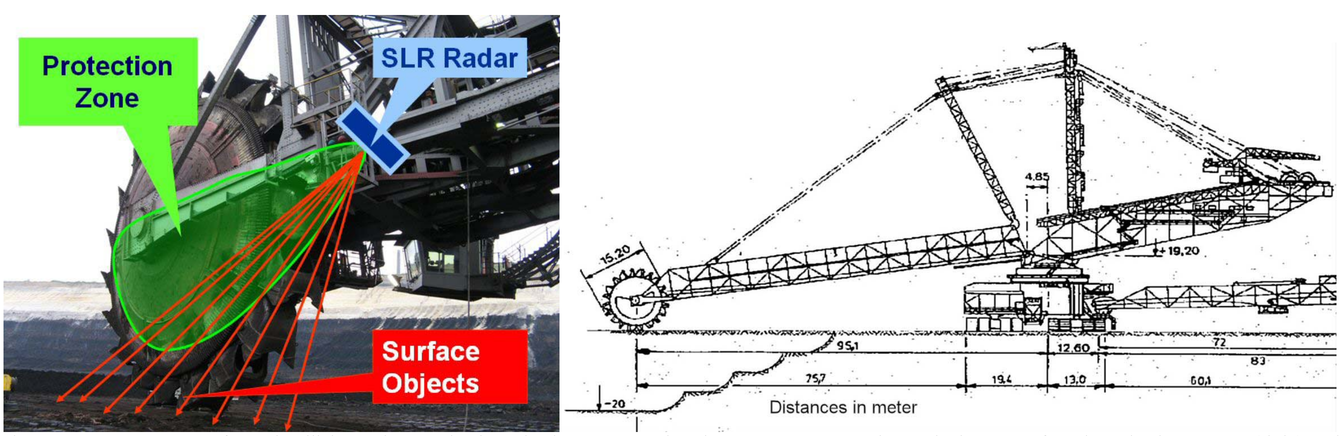

Fig. 4. Test arrangements for anti collision radar on a bucket wheel excavator using the SLR sensor. Drawing and Distances of Bucket wheel excavator (right) and target surveying zone for SLR sensor (left)

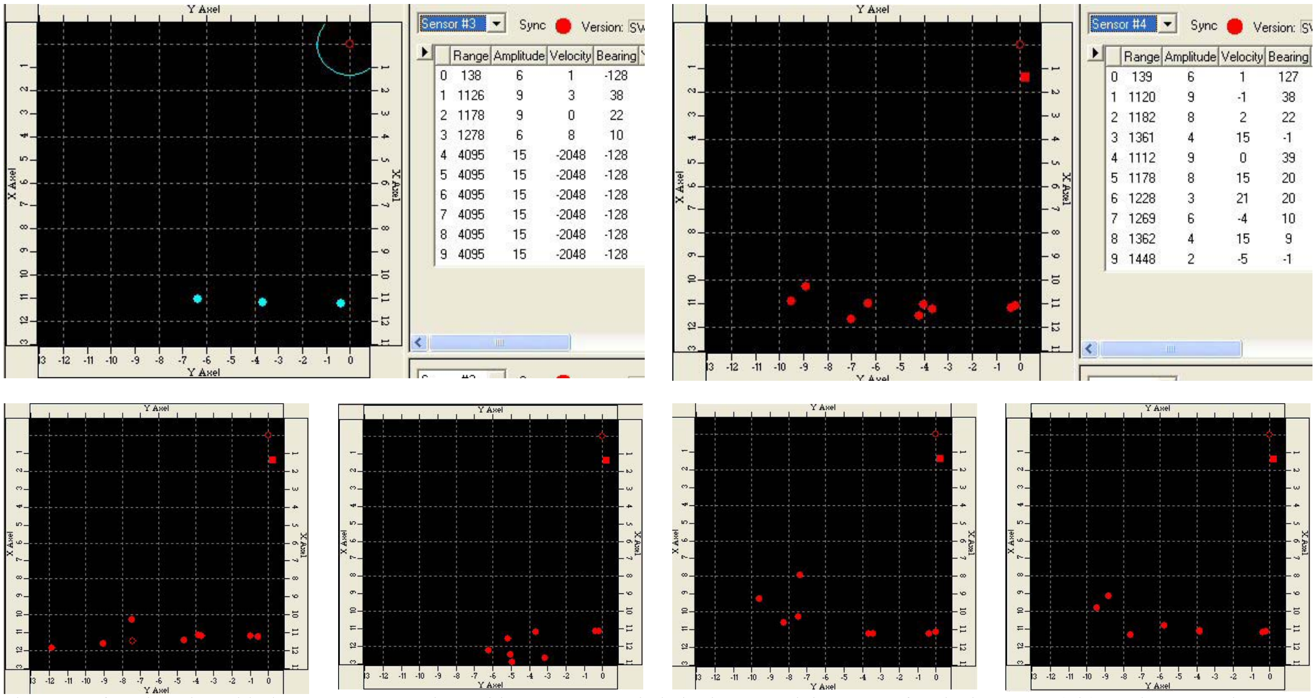

Fig. 5. Surface detection with the SLR sensor. Radar position as a empty circle in the upper right corner of each pictures on (0/0). Both axes are in meters, sensor about 11m over ground looking 40° to the left like shown in Fig. 4. Tracked objects are illustrated with the data table in the upper left screen shot (5a), untracked objects in the upper right screen shot (5b) and some additional untracked shots in the lower four radar screen shots (5c).

Within the test it was recognized, that tracking of objects is not valuable. With every little movement of the machine another piece is acting as a strong reflector depending on the orientation of the coal lumps, so that the tracking will loose the tracked objects from scan to scan. Hence the tracking algorithm is merging multiple objects to one so that only 2-3 objects are logged (Fig. 5a).

Based on the swing movement of the bucket wheel and the vertical radar installation all objects are passing the radar beam across the elevation. This confuses the algorithm as it was designed for automotive application where objects on the road are rather passing horizontal from one lane to the other than vertical from the sky to the ground.

The use of untracked data take as well more advantage of the capacity of 10 objects in the sensors memory (Fig. 5b). Due to the homogeneous RCS of the coal lumps, a different set of objects were determined with every new shot after 40ms (Fig. 5c). Moreover the figures are imaging only a few meters of the surface in objects in a band which ranges from about 10-15 meters. As the sensor is filling the object list by the signal amplitude, surface objects at higher ranges will disappear in the presence of several objects at lower range because of their path losses.

Furthermore, clutter objects which are appearing irregularly over the complete range. These are partially caused by side-lobe reflections of the steel structure but as well misinterpretations of the monopulse algorithm.

Due to the limited stability and precision of single shots averaging of the data over 5-10 shots would be required. The data could then be processed by an anti collision algorithm which stops the machine if an accumulation of objects is detected in a defined protection zone. To minimize the number of false alarms, the zone should be at least 2-3m smaller than the diameter of the bucket wheel.

To summarize, simple automotive radar systems can be used for collision surveillance in large mining equipment in simple and known geometries. However, they are not useful for terrain mapping.

IV. Mapping of Trench Contours

For mapping trench contours the experimental sensor was mounted on a movable working platform with its imaging plane set vertical (Fig. 6). The line of sight of the sensor is pointing downwards to the area to be observed. The radar images in Fig. 7 show a typical measurement result evaluated with different beam-forming methods for cross range processing. Using simple FFT cross range processing, the typical contour of an escarpment is becoming visible, but not sharply bounded (Fig. 7a). Better results are obtained with a nonlinear filter (Fig. 7b). In this technique the ratio of the sum and the difference of the sub-arrays formed by the scans recorded with the two receivers are evaluated [6]. The method is similar to mono-pulse processing, but not limited to one object per range cell. The resulting concentration of the point-spread functions makes the trench contour more sharply. A further improvement in the contour can be obtained using autoregressive prediction to extend the available array of scans by predicted elements (Fig. 7c). The synthetically extended aperture results in an improvement in cross range resolution (super-resolution technique). The latter method led to the best results in the field tests. The MUSIC algorithm as an example of noise subspace methods did not prove to be useful for cross range processing (Fig. 7d). Array tolerances are the possible

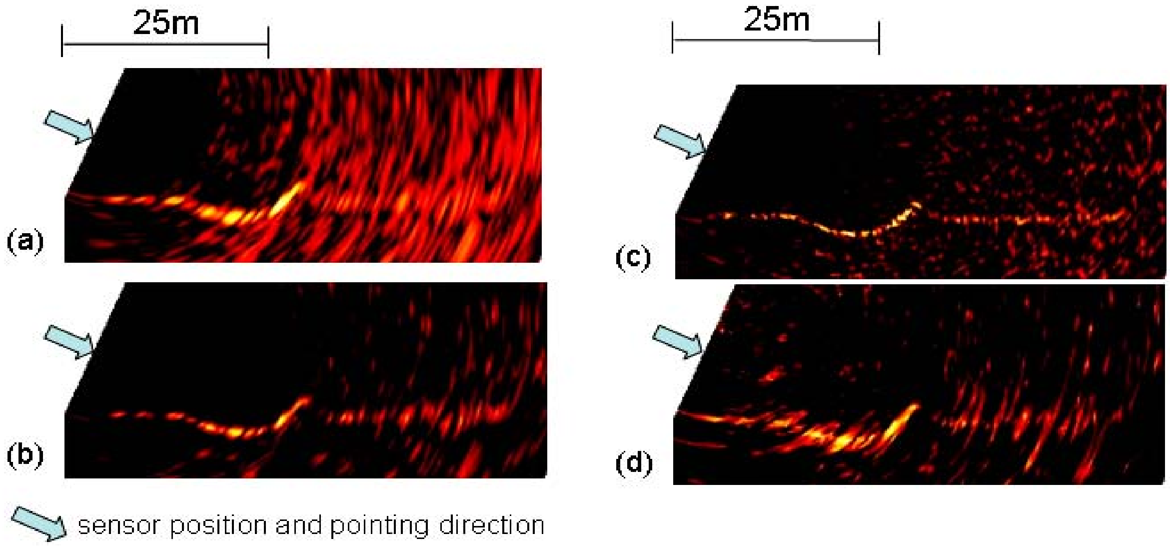

Fig. 7. Test results obtained with the HARFE system and the setup in Fig. 4 using different signal beam-forming techniques: (a) simple Fourier transform, (b) nonlinear filter, (c) autoregressive element prediction, (d) MUSIC algorithm. The color plots display the intensity of the radar response in dB with dynamic ranges of 30dB for the linear techniques in (a), (c) and 50dB for the nonlinear techniques in (b) and (d).

reason for this result. In [5] the applied beam-forming techniques are described in detail.

The results depicted in Fig. 7 are from one scan over all transmit elements with an over-all recording time of 5ms. This short measurement time is necessary to cope with fast moving objects in automotive applications. It limits, however, the target dynamic range at longer ranges (>25m). For update rates of 2-5Hz, required in industrial and mining applications, the recording time could be increased or many scans could be integrated resulting in a reduced noise and thus increased maximum range.

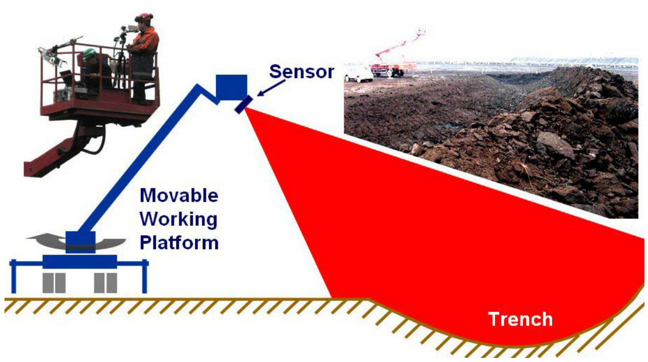

Fig. 6. Test arrangement for contour measurements with the experimental sensor.

V. Further results and outlook

Future research topics with the SLRs are in algorithms for reducing false alarms in the observed safety zone. It will probably be necessary, that the raw radar data (prior to the detection process) are applied to these algorithms. Concerning the experimental sensor, an antenna with a more narrow elevation beam would be of interest to explore 3D mapping of the area underneath the boom of a spreader.

VI. Conclusion

Two compact radar sensors with electronic cross range measurement have been evaluated for applications in surface mining machines. The experimental results have identified, that the simple SLR-sensor based on mono-pulse techniques is applicable for collision surveillance in some special arrangements. The experimental sensor using digital beam-forming techniques has shown the potential for various applications in the field of surface mining, as it is capable to map contours without mechanical scanning.

VII. Acknowledgment

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