Automated Characterisation of Multi-Channel Radar Antennas for Detecting Road/Rail Traffic Obstacles

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***Abstract*—This paper describes a 76-77 GHz radar sensor that is used for detecting obstacles at road/rail intersections. The paper describes some of the key aspects of the applications and the radar design, with emphasis on the need for good characterization of the radars' antennas. To meet this need, an automated characterisation procedure has been developed and is described in this paper.**

Keywords—radar, antenna measurements.

I. Introduction

To increase safety in traffic there is need for new technology to improve the detection of hazards that may cause serious accidents. This is particularly noticeable in the automotive industry, where sensors are usually placed on the vehicles themselves. However, for railways the speeds and braking distances involved usually require identification of hazards that cannot reasonably be detected from the vehicle. The most risk is at level crossings, where vehicles (cars, lorries, buses, etc.) as well as unprotected road users (pedestrians and cyclists) are at risk, see for example [1]. To detect these hazards requires infrastructure at the crossing, which can inform approaching trains of any hazards in time for them to slow down to avoid an accident.

In Sweden, the Swedish Transport Administration (Trafikverket) are currently in the process of evaluating the use of a radar-based system for detecting obstacles at level crossings [2]. Radars have significant advantages over optically based systems (i.e. cameras and lidars) in terms of their robustness to dirt and moisture (rain, snow and condensation) on the sensors. However, compared to automotive applications, where the radar is on a moving platform, the requirements on radar performance are quite demanding. This is because of the need to detect small stationary obstacles which are located in a stationary clutter background, i.e. Doppler information is of limited use. Aside from level crossings, these systems also have many applications where it is of interest to monitor a limited area as an alternative/complement to optical systems, e.g. for monitoring road junctions to support control of traffic lights, for security applications such as intruder alert, for enforcing safety zones around heavy machinery, etc.

To meet the requirements for a safety-critical system, the QR77SAW radar has been developed by Qamcom Research and Technology [3]. This radar uses complex array antennas to accurately detect and position potentially hazardous obstacles. In order to meet the requirements, it is important that the antennas used are well-calibrated, so an automated procedure for antenna characterisation has been developed. This paper gives a brief description of the QR77SAW radar, and how the design has been made to meet the requirements on an obstacle detection system for traffic infrastructure. In particular we focus on the main properties of the radar system that set requirements on the characterisation on the radars' antennas, the so-called steering vectors, which are essential to allow detection and localization of small objects. This is then followed by a presentation of the characterisation procedure used.

II. Requirements for Obstacle Detecting Radar

In this section we summarise some of the key requirements on sensors for obstacle detection at level crossings. How these are met in a radar sensor design is then discussed in the following section.

A. Coverage Requirements

Fig. 1 illustrates schematically a level crossing. In order to be able to detect obstacles present when the barriers are closed the sensors ideally have line-of-sight over the crossing. Furthermore, they need to be placed outside of both the road and railway to avoid obstructing traffic, hence they are typically situated at the corners of the crossing. In this example diagonally opposite corners are used, to ensure good coverage of the whole crossing, and to give some redundancy between the sensors. Given this geometry it can be seen that an angular coverage of about 90^{o} is required, and that the typical range to be covered is from very short range (a few metres) up to the diagonal of the crossing (about 30 metres). Furthermore, the sensors should a cover a volume up to the height of possible obstacles (about 3 metres), to include the detection of objects which may protrude into the crossing from outside (e.g. cranes sticking out in front of a truck).

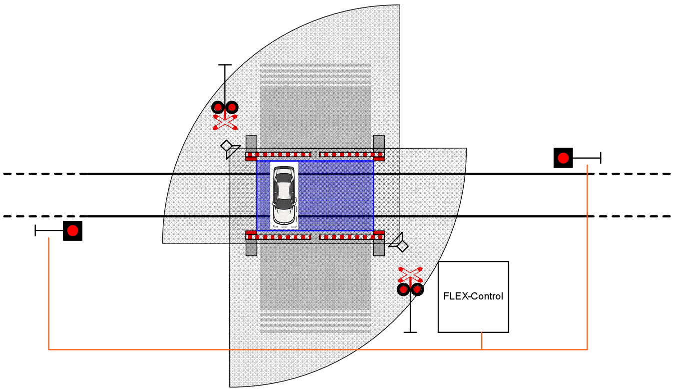

Fig. 1. Schematic illustration of a level crossing. The road runs from top-to-bottom, and the railway from left-to-right. In this example a car is shown obstructing the railway, even though the barriers are closed. Two sensors (radars) are illustrated on opposite corners, which are combined to control the level crossing (denoted FLEX-control), which could then activiate signals at some distance from the crossing to warn approaching trains.

B. *Positioning accuracy*

An important requirement on the sensor is that it can accurately position any objects that are detected, primarily this is a case of determining whether the objects are inside of the closed barriers or not. The sensor should not report any objects which are outside of the barriers, but cars and pedestrians can approach very close to barriers. Since the distance between the barriers and the rails is of the order of a few metres, the position of any potential obstacles needs to be determined with a sub-metre accuracy. At a range of 30 metres, this gives a angular positioning requirement of about 0.01 radians (for 30 cm accuracy), i.e. ~0.6 degrees.

C. *Safety and availability requirements*

The system developed needs to reliably detect objects which can result in a serious accident. A detailed discussion of the safety requirements is outside the scope of this article, but we note that even relatively small objects (such as pedestrians) should be detected with high reliability (better than 99% detection rate). At the same time, the rate of false alarms must be kept low in order to avoid disruption of train traffic, delays, etc.

An operational system for monitoring railways must be able to operate continuously, regardless of weather conditions. Hence the system must be extremely reliable. These requirements suggest the use of a radar rather than an optical system, and that the system should avoid mechanical movement.

III. RADAR DESIGN

A. *Hardware*

The radar design is based on 76-77 GHz radar chips developed for automotive applications, [4]. In general, lower frequencies have better weather tolerance to poor weather, but higher frequencies make it possible to reach a high angular resolution with a smaller system. The W-band has been chosen as giving a good balance between these considerations. Furthermore, the use of these chips in automotive applications means that there is a wide choice available at reasonable cost. To achieve high position accuracy and resolution multiple channel processing is performed, using a wide transmit beam and then array processing on receive to get direction estimates.

Fig. 2 shows a picture of the radar front-end, where the transmitter antennas are shown, as well as the eight receiver channels. The patch antennas are designed to give wide lobes in azimuth, and the patches are placed in columns to give a tapering resulting in a good elevation pattern to cover the required crossing. The transmitter combines two columns to produce an azimuth pattern that covers the main area of interest; note that three pairs of Tx antennas are available for time multiplexing of three different Tx beams.

At the receivers, the signal is mixed with a copy of the transmitted waveform to produce a base-band signal. This signal is filtered and amplified (with a low-noise amplifier), before converting to digital signals in an analogue-to-digital converter (ADC). The digital signals are then passed to the signal processing unit on a second printed circuit board (PCB). The digital signals pass through a field-programmable gate array (FPGA) for pre-processing, then to a multi-core digital signal processor (DSP). The signal processing unit also includes ARM cores for controlling the front-end, tracking of detected signals, and communicating with other systems via Ethernet and PROFIBUS.

B. *Radar Signal Processing*

The radar is a frequency-modulated continuous wave (FMCW) system, with a chirp bandwidth equivalent to approximately half of the available bandwidth in the 76-77 GHz frequency band. Furthermore, the centre frequency of the sweep can be changed to allow the systems to reduce interference (from other obstacle detecting radars in the level crossing, and from automotive radars on vehicles that may be waiting at crossing) so that the full bandwidth of the system is utilised.

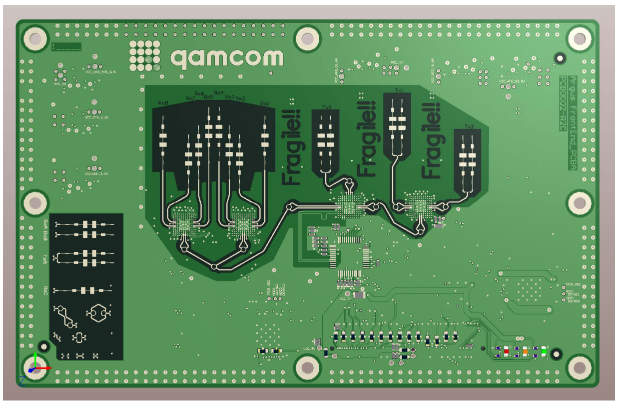

Fig. 2. Picture of the radar front-end, showing the positioning of the transmit antennas (Tx) and receiver antennas (Rx).

The initial processing steps are some checks that the signals are not saturated or suffering from too much radio-frequency interference (RFI) from other radars operating in the same frequency band. Some mitigation schemes are used to handle RFI to avoid producing false alarms without significantly reducing the sensitivity to detect small objects.

Fig. 3 gives an overview of the main blocks in the signal processing. After pre-processing, FFTs are used on each of the eight channels to transform data to a range-Doppler domain. The eight channels are then used in the detector to identify objects which differ from the "background". The background here is a representation of the obstacle-free crossing, which must be updated to account for the continuous changes that occur as the environment changes. Note that the background updates cannot be performed when there are obstacles, or even suspected obstacles in the zone, and the procedures for determining when it is safe to update the background are vital to the successful operation of the system.

In the detection process we use a generalized likelihood ratio test (GLRT), in a similar manner to [5], to test the hypothesis of an obstacle being present compared to the null hypothesis (no obstacle), where the null hypothesis is represented by the covariance matrix of the background. The covariance matrix needs to be updated to deal with changes in the environment (e.g. vehicles outside of the crossing, moving barriers when the level crossing is closing, changing weather conditions), while not including potential obstacles within the crossing.

To focus the received signals in angle, we use reference "steering vectors". The steering vectors represent the received signals in the eight channels coming from a source of unit amplitude. Hence by matching the steering vectors to the incoming signals it is possible to focus the energy and determine the direction to the scattering object(s). The steering vectors are in principle a function of the antenna design (i.e. positions of antenna patches shown in Fig. 2. In practice, however, small differences in production of antennas and feed lines into the receivers' mixer, reflections in the radome and interactions between Rx channels and other components on the front-end PCB mean that the true steering vectors differ somewhat from the models. Furthermore, the requirements on the knowledge of the steering vectors are high in this application, where we not only need to find the angular position of the scatterers, but also need to be able to cancel strong signals from other scattering objects at the same range but different angles, since the majority of scattering objects are stationary when the level crossing is active (barriers closed).

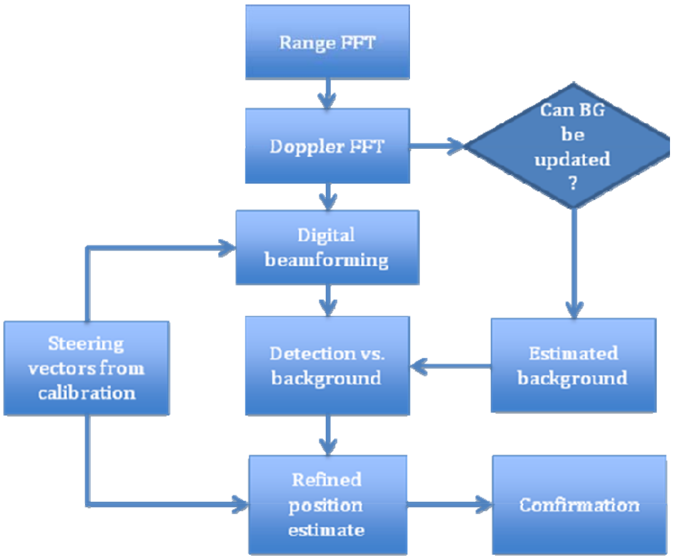

Fig. 3. Block diagram of signal processing in the radar (excluding tracking function).

Following the detection process in the signal processing a tracker based on Kalman filtering is used to improve the reliability of the system and allow higher-level decisions about whether objects constitute a hazard for approaching trains.

IV. ANTENNA CHARACTERISATION

A. Characterization method

As discussed in the previous section, it is essential that the steering vectors representing normalised received signals from different directions are well defined in the signal processing. The key to this is a factory measurement of the appropriate steering vectors. To perform these measurements a dedicated measurement facility has been built.

The principle for the measurements is to use a large trihedral reflector to provide backscatter with a strong signal-to-noise ratio (SNR). The backscatter is measured with the trihedral at different directions from the radar, which is accomplished by rotating the radar using a mechanical turntable (2-axis). To ensure high signal quality the radar and turntable is enclosed in an anechoic chamber which is only open towards the reflector (see Fig. 4).

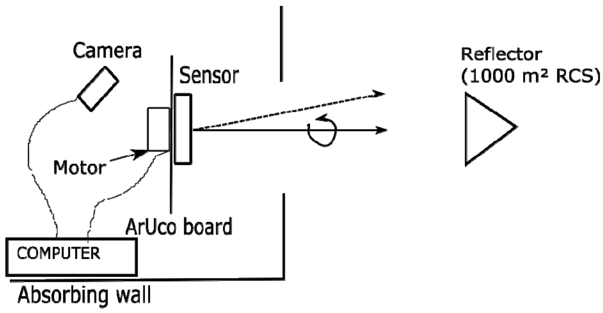

Fig. 4. Schematic of the measurement setup.

For high-quality characterization of the antenna, it is paramount that the radar can be positioned in a desired orientation relative to the reflector with a high level of precision. For this purpose, a 2-axis motor is used in combination with a computer vision system based on ArUco markers [6],[7].

The motor enables rotation of the radar around a vertical axis (pan), as well as around the phase centre of the receive antenna (roll). During measurement, an aluminium board with printed ArUco markers is mounted on the motor in such a way that it rotates together with the radar. A camera situated at an angle behind the motor continuously films the board and transfers the images to a computer. The pose (rotation and displacement) of the board relative to the camera is subsequently estimated by a control program, and the orientation of the board, and thereby also the radar, relative to the reflector is calculated using the position of the reflector relative to the camera (this information must be provided by the operator).

With feedback from the computer vision system, the pose of the radar can be adjusted iteratively rather than relying on the precision of the motor. The precision in the pose estimate given by the computer vision system is approximately 1 milliradian, so measurement points a few milliradians apart can be reliably separated. Characterization of the antenna can thus be performed for a dense grid of measurement points in azimuth and elevation. In practice, a measurement grid consisting of 4500 points and a grid spacing of about 20 mrad has been found sufficient to fulfil the angular positioning requirements on the radar.

We note that in practice it also important to include the fact that steering vectors vary with transmit frequency, and hence the measurements are made with chirp signals that are the same as used in the detection process.

B. Characterization results

To exemplify the results of the antenna characterization method described above, results from characterization of one QR77SAW unit can be seen in the following figures. Fig. 5 shows the total two-way gain in dB as a function of the directional cosines *u* and *v*. Here, *u* is defined as the ratio of the horizontal coordinate of a target to the distance from radar to target, and *v* is defined as the ratio of the vertical coordinate of the target to the distance from radar to target.

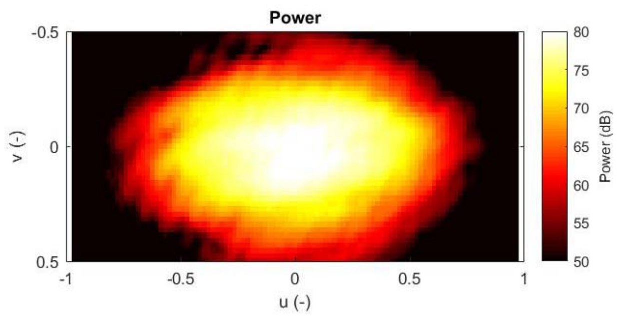

Fig. 5. Two-way gain of QR77SAW, from characterization measurement.

Fig. 6 shows the phase in radians as a function of *u* and *v* for each receiver channel. Note that the fifth channel is used to normalize the phase, hence it has a phase value of zero for all points.

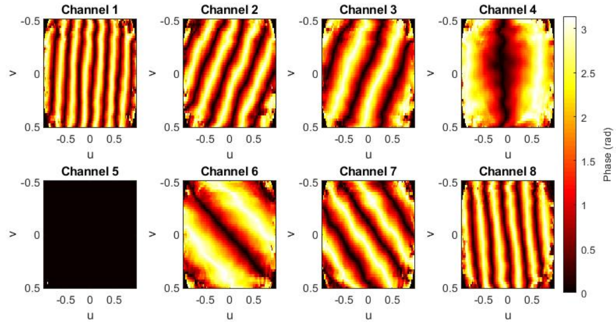

Fig. 6. Absolute value of the phase in radians for each receiver channel in QR77SAW as function of *u* and *v*.

V. FINAL REMARKS

In this paper, a 76-77 GHz radar sensor for monitoring road/rail intersections has been described. In addition, a method for characterizing the sensor antennas is presented. The characterization method is necessary to achieve the high angular resolution required for the present application.

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