A Novel Direct-Imaging Radar Sensor with Frequency Scanned Antenna

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***Abstract* — Principle, design and experimental results of a simple direct imaging radar sensor are presented. The FM-CW radar principle and a frequency scanned antenna are combined with waveforms of different frequency slopes in such a way that angular and range information are provided by the amplitude envelope of a fixed video frequency. The sensor architecture uses a minimum of active RF components and digital signal processing. With low cost frequency scanned antennas this architecture can be applied in radar surveillance stations or automotive side looking sensors.**

***Index Terms*— Radar Sensors, FM-CW, frequency scanned antenna, surveillance station, automotive sensors.**

I. Introduction

FINDING low cost solutions for cross range resolution in commercial radar sensors is a continuous research problem [1]. Antennas changing the main beam angle with the frequency of the applied signal [2] are one means to get cross range resolution. Their advantages over mechanical scanning techniques are very high scan rates and the avoidance of mechanical wear. Compared to phased array solutions, their complexity and cost are moderate.

Using the combination of FM-CW radar and frequency scanned antenna, range and angular information is gained by the same modulation simultaneously. As both information depend on one quantity, however, a compromise between range and cross range resolution must be found. Furthermore, special means have to be applied to extract concurrent range and cross range information from the received intermediate frequency (IF) signal. In [3] a high performance ground mapping radar is presented using a standard FM-CW architecture combined with a frequency scanned waveguide slot antenna [1] and special signal processing. To get angular information, the low pass filtered IF signal is transformed piecewise by a fast Fourier transformation into range scans corresponding to particular angular sections.

In the radar concept presented in this article, successive cross range scans for particular range gates are recorded, and frequency analysis is performed by a fixed IF bandpass filter and adjustable frequency slopes [8].

II. Sensor Principle

The principle block diagram of the sensor is shown in Fig. 1. The frequency modulated waveform generated by the modules (A-C) is applied to the frequency scanned antenna (F) and to the LO port of the receive mixer (G) via a passive power divider network (D,E). Reflected signals received by the antenna are coupled to the RX port of the mixer. The mixer IF output signal is filtered by a bandpass filter (H), amplified (I) and demodulated by an envelope detector (J). The demodulated signal is then applied to an analog to digital converter (K) to be able to collect and visualize (M) the radar image information by a microcontroller (L), which controls at the same time the measurement sequence.

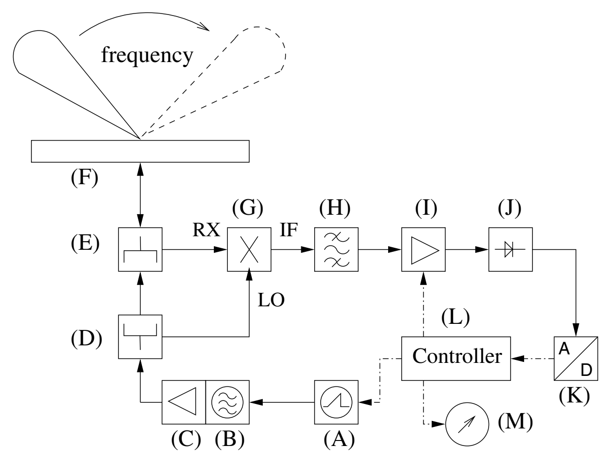

Fig. 1. Functional Block Diagram

In Fig. 2 the measurement sequence is depicted for two exemplary point targets T_1 and T_2 with range and cross range coordinates (R_1, ϕ_1) and (R_2, ϕ_2), respectively. Diagram (a) shows the transmit frequency of four sawtooth waveforms with different slopes S. The direction of the main lobe of the frequency scanned antenna follows the transmit signal frequency as depicted in diagram (b). According to the known FM-CW range equation

$$f_{\mathrm{IF}} = S \cdot \frac{2 \cdot R}{c_0} \quad (1)$$

the targets are causing IF signals IF_1 and IF_2, as indicated

in diagram (c). These IF signals are present only while the main lobe of the frequency scanned antenna illuminates the particular target.
In that way angular target coordinates can be derived from the existence of an IF signal during the modulation time, and range positions typically are extractable from the IF signal frequencies. By applying a fixed frequency bandpass filter (i) to the IF signal, the resultant filtered IF for a specific range gate is cut out as shown in diagram (d). Now, by adjusting the waveform slope, the observed range gate can be changed and the radar sensor provides an angular scan of one distinct range gate (j) for every frequency slope (e). By a series of waveforms with different slopes, a two-dimensional radar image can be recorded directly by detecting the amplitudes of the fixed frequency IF signal.

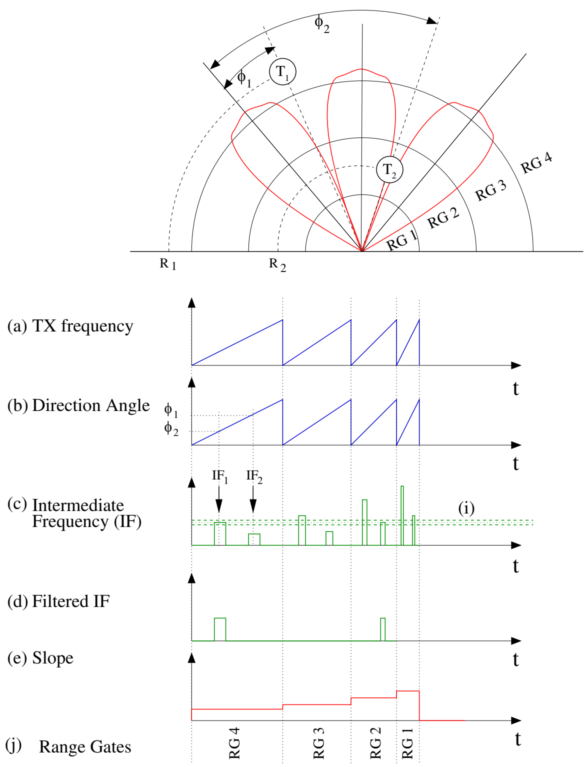

Fig. 2. Measurement Procedure

III. Design Considerations

The combination of FM-CW radar and frequency scanned antenna forces a compromise between angular and range resolution. For an angular resolution given by the 3dB bandwidth of the antenna of $\Delta\phi = \phi_{3\text{dB}}$ and the antenna scanning sensitivity $S_A = \frac{d\phi}{df}$, the range resolution ΔR for a point target is given by

$$\Delta R = \frac{c_0 \cdot S_{\text{A}}}{2 \cdot \Delta\phi} \,. \tag{2}$$

In [1] this context is well summarized to a target uncertainty

$$\Delta\phi \cdot \Delta R = \frac{c_0}{2} \cdot \frac{d\phi}{df} = \frac{c_0}{2} \cdot S_{\text{A}} \,. \tag{3}$$

The only means to cope with this limitation is either to find a satisfying compromise for the given application or to use two different frequency scanning antennas, one with narrow beam width for high angular resolution and the second with broad beam width for high range resolution.
Another important design issue is indicated by the evaluation of the relationship of the frequency slopes S for different range gates R using a fixed intermediate frequency f_{IF} given by

$$S = \frac{f_{\text{IF}} \cdot c_0}{2 \cdot R} \,. \tag{4}$$

Being a hyperbolic function of R the slope S is dramatically increasing for very short ranges. This results in very low dwell times of targets in the antenna main lobe (time on target, T_{ot}) and thus in very short IF signal durations (Fig. 2, diagram (c)). Very short IF signals however, require a broadband IF bandpass filter to be detected. As frequency and bandwidth of the IF filter are to be kept constant for all ranges to be measured, the IF filter bandwidth B_{IF} is given by the time on target T_{ot} at the lowest range. For longer ranges resolution degrades according to

$$\Delta R = R \cdot \frac{B_{\text{IF}}}{f_{\text{IF}}} \,. \tag{5}$$

To get satisfactory constant resolution over a given range interval ($R_{\text{min}}, R_{\text{max}}$) the ratio $B_{\text{IF}}/f_{\text{IF}}$ should be chosen as low as possible. Applying this, together with (3), leads to a minimum range given from the antenna parameters and the bandwidth to frequency ratio of the IF

$$R_{\text{min}} = \frac{c_0 \cdot S_A}{2 \cdot \Delta\phi} \cdot \frac{f_{\text{IF}}}{B_{\text{IF}}} \,. \tag{6}$$

Thus range resolution of the radar sensor is satisfactory starting from a minimum range R_{min}. In applications with a minimum physical range of zero, the problem can be overcome by using signal delay elements in the transmit or receive path of the sensor.
Further boundary conditions for f_{IF} and B_{IF} given by component properties are phase and amplitude noise of the receiver, linearity of the VCOs frequency tuning curve and quality factors of the IF bandpass resonators.
To compensate signal amplitude over range, IF amplifier gain can easily be adjusted from range gate to range gate. Yet another more advantageous way is to chose B_{IF} lower than $2/T_{\text{ot}}$. In that way, signal energy for short ranges is attenuated by the under matched bandwidth, and absolute range resolution is improved according to (5).

IV. Realization of an experimental system

To verify the sensor principle an experimental system was built. Due to the availability of a frequency scanned antenna [2] and an integrated 20-26 GHz RF module provided by EADS [4] the operational frequency is chosen to be 20 GHz. The given antenna provides a beam width of $\Delta\phi = 10°$, a maximum scan angle of $\Delta\Phi = 50°$, and a scanning sensitivity of $S_A = 111°/\,\text{MHz}$.
As a result of component related boundary conditions, f_{IF} is chosen to $50\,\text{kHz}$. Taking into account the considerations discussed in section III, the experimental sensor is designed to operate over the full antenna scan angle for ranges from $R_{\text{min}} = 15\,\text{m}$ to $R_{\text{max}} = 35\,\text{m}$. Range amplitude compensation is performed in the IF path by both, an adjustable gain amplifier and an under-matched IF bandwidth of $B_{\text{IF}} = 2.3\,\text{kHz}$. For the IF filter, an active 8th order Bessel design is applied. The filtered and amplified IF signal is rectified and logarithmically amplified by a standard logarithmic detector IC.
Control of the frequency slope is provided by a combination of DDS (Direct Digital Synthesizer) and PLL similar to [5].

Because of the antenna frequency range, the RF module has to be operated at its lowest frequency limit, and only moderate noise figure and low transmit power can be realized in the experimental setup. So it is necessary to separate transmit and receive antenna and to include an additional low noise amplifier (LNA) to get satisfactory target dynamic range. For the receive path, an antenna with a broad diagram covering the whole scan angle of the frequency scanned transmit antenna is used. The improvement in noise figure due to the LNA by far over-compensates the loss of the receiver antenna gain.
Control of the measurement sequence, and collection and visualization of image data are done by a PC and an oscilloscope.

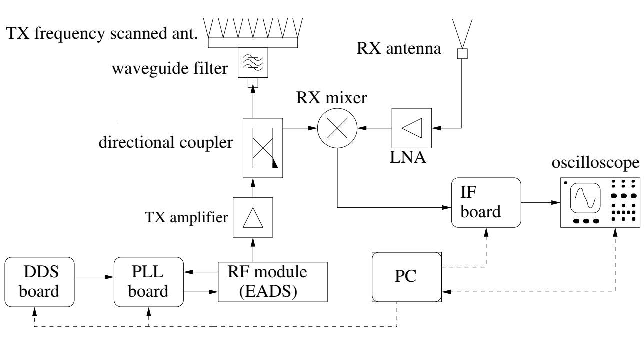

Fig. 3. Final Test Setup

V. Experimental Results

In this section some radar images obtained with the final experimental setup (Fig. 3) as described in the previous sections are presented. In the images, the recorded IF signal power values normalized to the respective maximum target are depicted (intensity coded) versus planar coordinates x an y. Fig. 4 shows a radar image for three targets, two reflectors and the wall of a building. To verify the idea of realizing a sensor with a minimum range starting from zero, a coaxial delay line of about 34 m electrical length is included before the antenna in the transmit path and an indoor short range measurement is performed. Fig. 5 illustrates the results for two reflector targets at different angles and short ranges. In Fig. 6 the radar image of a scene with an open garage door is shown. A corresponding photograph of the scene is in Fig. 7, and the geometrical arrangement is depicted in Fig. 8.

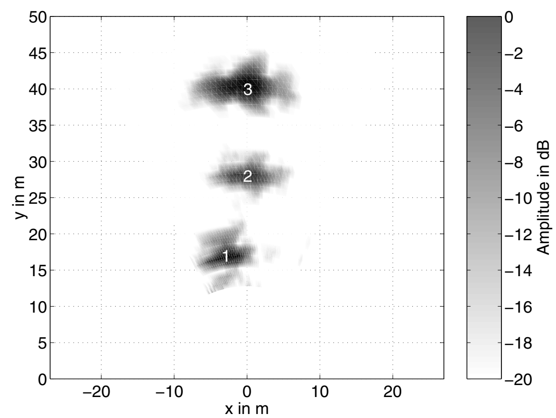

Fig. 4. Radar image of a three target scenery containing reflectors at positions 1 and 2 and the wall of a building at position 3.

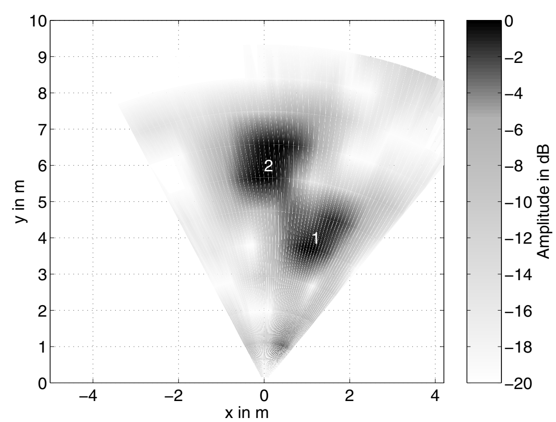

Fig. 5. Radar image obtained from two reflector targets (1,2) by measurement with delay lines in the transmit path to obtain zero range offset.

Albeit only a limited target dynamic range could be gained by the experimental setup, general functionality of the proposed radar concept could be verified.

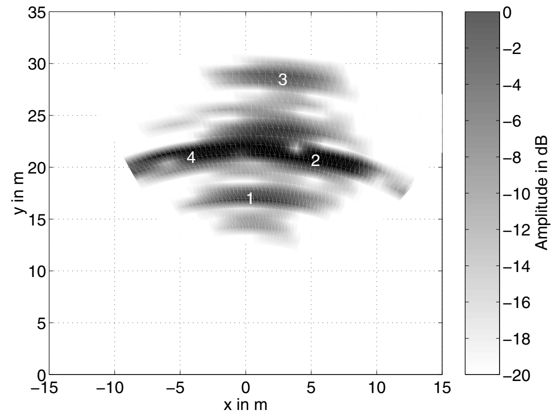

Fig. 6. Radar image of the open garage scenery shown in the photograph Fig. 7. Identifiable targets are a reflector (1), the garage door (2), the inside wall of the garage (3) and metal stairs left side (4).

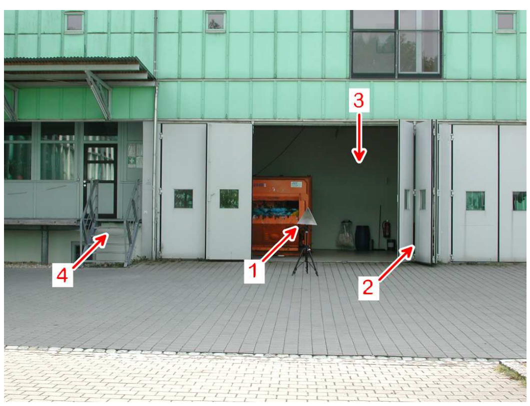

Fig. 7. Photograph of the scenery recorded in Fig. 6

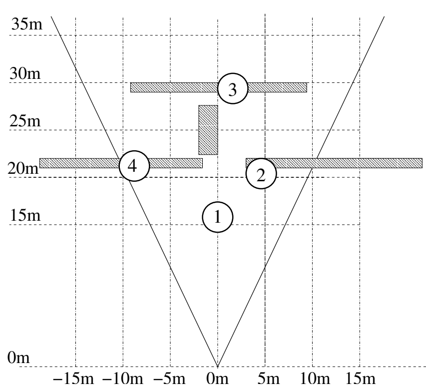

Fig. 8. Geometrical arrangement of the reflective elements corresponding to Fig. 6 and 7

VI. Conclusion

Architecture, design and experimental results of a simple direct imaging radar sensor have been presented. The sensor principle forces a compromise between range and cross range resolution, but provides both, range and cross range information using a minimum of active RF components. To use the concept for ranges starting from zero, additional signal delay elements have to be inserted into the radar sensor. It is planned to realize these delay elements by SAW devices according to [6].
Usefulness of the sensor for commercial radar applications will depend on availability of low cost frequency scanned antennas. There are ideas on realizing them as slot arrays based on substrate integrated wave guides or as metalized plastic injection moulded waveguide arrays [7].

Acknowledgments

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