MILLIMETER WAVE RADAR SENSOR FOR AUTOMOTIVE INTELLIGENT CRUISE CONTROL (ICC)

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ABSTRACT

An all-weather automotive MMW radar sensor is described that uses an FMCW radar design capable of acquiring and tracking all obstacles in its field of view. Design trade-offs are discussed and radar sensor test results are presented along with the applicability of the radar to collision warning systems.

INTRODUCTION

A millimeter wave radar sensor exploiting recent advances in MMIC and IC technology has been developed for ICC applications. For this purpose, it must perform two important functions. The first is to correctly locate a lead-vehicle being followed, constantly differentiating between the lead-vehicle and competing vehicles and roadside objects. The second is to report the distance and relative speed of the lead vehicle to the platform vehicle speed control unit, with constant updates at a specified rate. The ability to collect, process and keep track of information on the distance, relative speed and angular position of all objects in its field-of-view enables this sensor to correctly interpret situations which would otherwise result in faulty analysis of ambiguous data. Table 1 summarizes its performance specifications and Table 2 lists several options considered in developing the system architecture.

SENSOR HARDWARE DESIGN

Figure 1 shows the sensor block diagram, and Figure 2 shows the physical package. The radar generates an FM-CW waveform using an InP Gunn-diode voltage controlled oscillator (VCO). Samples of the output supply the receiver with its first local oscillator and provide feedback for the frequency control circuits. The waveform consists of positive and negative slope frequency ramps and fixed-frequency intervals. During each fixed-frequency interval, the VCO is phased locked to a harmonic of a clock oscillator. The ramp portions are linearized using a sample of the VCO output frequency fed to a SAW delay line interferometer producing an output signal proportional to the slope of the ramp. This signal's frequency is compared to a fixed reference to generate an error signal that corrects the VCO slope.

The radar uses a bi-static antenna system, obtaining approximately 80 dB of transmit-receive isolation to prevent receiver desensitization. The two antennas are printed circuits mounted on the front face of the radar enclosure and covered by a flat radome. The antenna produces several overlapping beams to cover the field-of-view and employs sequential lobing techniques in order to locate targets in azimuth. The novel printed circuit antenna consists of a Rotman-Turner Lens beamformer and an array of

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series-fed patch antennas built on a 5-mil thick soft-substrate material. Beam position is controlled by electronically switching the Rotman-Turner Lens feed point. This provides relatively fine spacial resolution and a broad field-of-view while minimizing volume and aperture size. With this approach we have built antennas that provide an azimuth coverage of 8.8 degrees using 4 beams and 15.4 degrees using 7 beams, each with an individual beam width of two degrees. The radar is currently instrumented with a four beam antenna The elevation beam width is fixed at four degrees to allow for vehicle pitch and variations in road inclines. A 7-beam antenna and its performance is shown in Figure 3.

The present receiver design is a superheterodyne, although a switched homodyne approach may also be used. Only a modest noise figure (of the order of 10 dB) is required in order to achieve the necessary signal to noise ratio for vehicular targets (including motorcycles and pedestrians) within the 100 meter range. The output of the receiver is fed to a 12-bit analog-to-digital converter, which becomes the input to the digital signal processor.

Analysis of received power levels from vehicles of various cross sections and from clutter (Figure 4) shows that the radar's sensitivity is sufficient to detect a vehicle as small as a motorcycle (1 sq meter) at 100 meters range and that the dynamic range of the receiver is sufficient to accomodate the entire range of expected signal returns.

ALGORITHMS

The algorithms used in the digital signal processor track all the objects in the field of view. Based upon the recent history of a given target, they predict an object's range, range rate, and acceleration at the time of the next radar action. Angular information is derived from the presence of the object in different (azimuth) antenna beams. The radar chooses the nearest target, satisfying certain acquisition criteria, as the lead vehicle. The radar then reports this vehicle's spatial parameters to the platform's computer.

It is essential to distinguish curves from lane changes. A lead vehicle in a curve should be followed, but one that leaves the platform vehicle lane should be dropped. Lane estimation uses platform yaw rate, moving vehicle tracks, and stationary object tracks. This data is used in three independent lane estimators, each of which determines an estimate of the lane ahead of the platform vehicle and an associated uncertainty. These estimates are then statistically fused to create a composite lane estimate.

ALIGNMENT

Because it is important to align the antenna boresight to the platform vehicle longitudinal axis, and it is not cost effective to maintain precise mechanical alignment, the sensor incorporates an electronic self-alignment feature. This is accomplished with three additional antenna elements. The transmit antenna radiates a horizontal fan beam onto the ground in front of the vehicle at 45° from the horizontal. The two receive antennas produce vertical fan beams aimed to the right and left of the center line, intercepting the transmit beam at two spots on the ground where the beams intersect. Doppler offsets from the two received signals yield the information required to calculate the sensor's normal compared to the vehicle's line of travel for correction in the signal processor.

TESTING

Extensive open-loop testing on a moving platform was performed on US interstate-type highways and included all vehicle types, weather conditions, and clutter environments. Excellent vehicle tracking performance was observed for cars, trucks, motorcycles and pedestrians. The instrumentation included a computer, a video camera and recorder, a data recorder and a display. Figure 5 shows a freeze frame from the real time tracking display used for open-loop sensor testing. With this system, sensor range, relative speed and angle to the lead-vehicle are reported numerically, positioned below the video image of the roadway ahead. A cursor, overlaid with the video image, provides a constantly updated visual indication of the vehicle under track. Also included on the display screen is a real-time graphical representation of the sensor's field of view using triangles to represent the position of all obstacles under track. Horizontal tick marks represent distances of 25, 50, 75 and 100 meters. The direction of each obstacle's radial velocity is indicated in the diagram by the direction the triangle is pointing (opening or closing range).

CONCLUSION

Raytheon has developed a forward looking automotive radar sensor for ICC. The requirements for these applications are driven by the need for high resolution spatial selectivity in range, relative speed and angle. The recognition of spatial selectivity as a key element in a robust ICC system has yielded a design whose performance will also meet the needs of forward-looking collision warning systems.

Raytheon is currently working on a new version of the sensor design to reach production cost goals. This will be accomplished by introducing MMIC technology in the transmitter and receiver front end, and employing a simpler (chopped homodyne) downconversion.

Table 1. Performance Specifications

Characteristic	Value
Operating Frequency	76-77 GHz
Waveform	FM-CW
Range	3-100+ meters
Range Accuracy	<0.5 meters
Relative Speed	± 160 Km/hr
Relative Speed Accuracy	< 1.5 Km/hr
Update Rate	20 Hz
Field of View (Azimuth)	8.8 degrees
Field of View (Elevation)	4 degrees
Max. Targets Under Track	40
Interface	RS-232, High-Speed Parallel

Table 2. Sensor Tradeoffs

- **Waveform**
  - ✔ **FMCW**
  - – **Pulse Doppler - Complex & Expensive**
- **Antenna**
  - ✔ **Separate Tx/Rx (Bi-Static) - Dynamic Range, Sensitivity**
  - – **Single Antenna**
  - – **Quasioptical**
  - – **Waveguide**
  - ✔ **Microstrip - High Performance, Low Profile (Minimum Volume), Low Cost**
- **Antenna Scanning**
  - ✔ **Switched Beams**
  - – **Mechanical - Reliability Issues**
  - – **Frequency - Complexity (Waveform Limitations)**
  - – **Phase - Development Cost & Lead Time, Production Cost**
- **Transmitter**
  - ✔ **Gunn Oscillator (Present Approach)**
  - ✔ **HBT, PHEMT MMIC Oscillator (Planned Approach)**
- **Receiver**
  - – **Homodyne - Poor Noise Performance**
  - ✔ **Heterodyne (Present Approach)**
  - ✔ **Chopped Homodyne (Planned) - Less Complexity Than Heterodyne; Requires MMW LNA**
- **Signal Processing**
  - ✔ **Digital Processor**
  - \- **Analog Filters - Hardware Complexity & Cost**

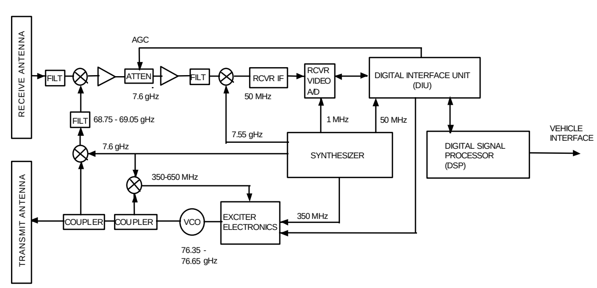

Figure 1. Radar Sensor Block Diagram

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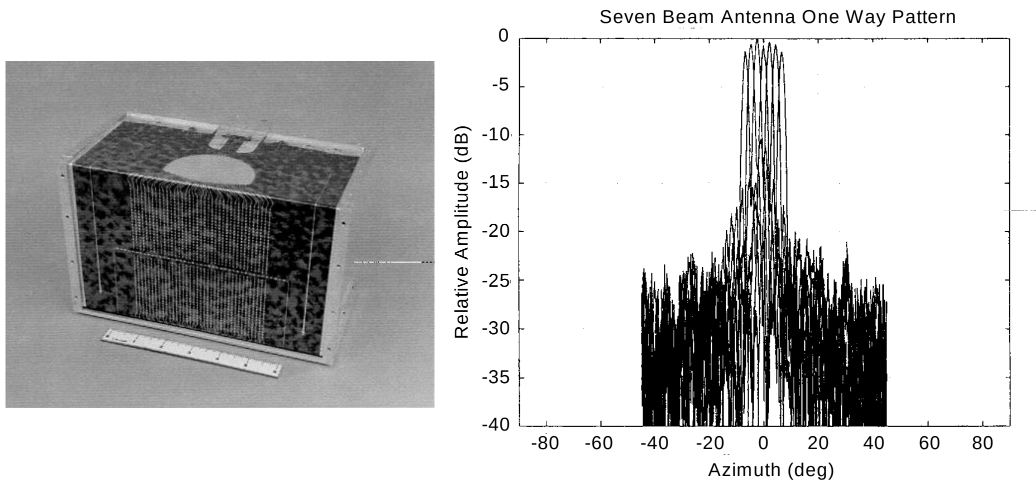
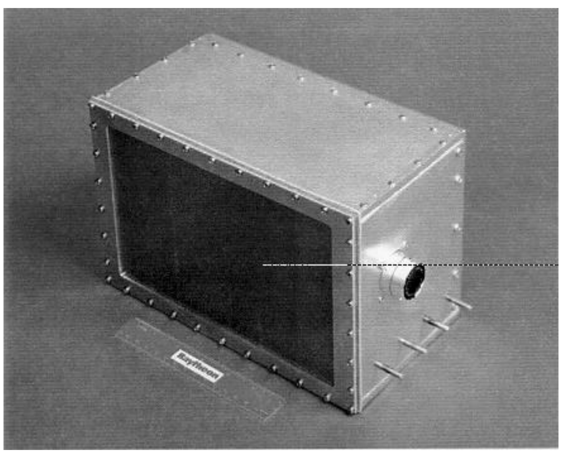


Figure 3. Antenna Design and Performance



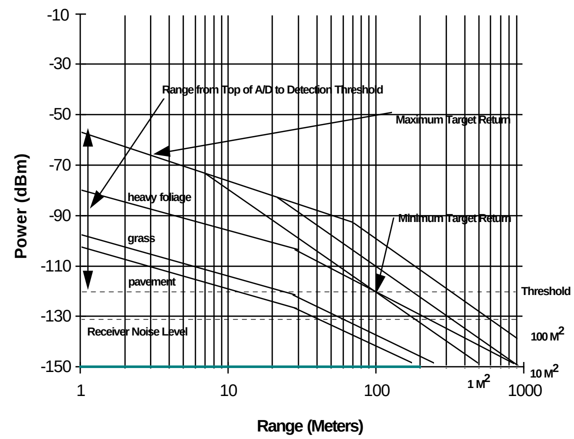


Figure 2. Radar Sensor Package **Figure 4. Signal and Interference Levels**

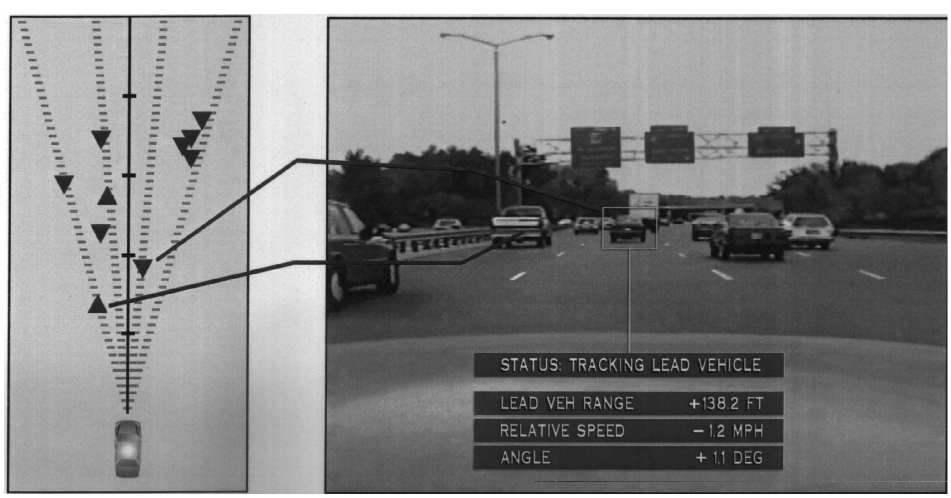


Figure 5. Real-Time Tracking Display