A VERSATILE 77 GHZ. SCANNING RADAR SYSTEM.

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Abstract.

The design, construction and performance of a single channel FMCW scanning radar system is described. This system consists of three integrated assemblies - a high gain antenna with a 360-degree scanning periscope sub-reflector, the 77 GHz. Tx/Rx sensor and the signal processor/system controller.

By using many of the design and constructional features developed from the ACC cruise-control automotive 77 GHz. car radar sensor, [ref.1], the Tx/Rx sensor construction is robust and suitable for low cost quantity production. The signal processing system was designed for real-time sampling and processing of the FMCW radar signals supplied from the sensor, [ref.2]. These radar IF signals can also be viewed and further processed remotely through a high-speed data link.

This system has been demonstrated in a variety of industrial sensor applications, viz., High accuracy navigation of autonomous industrial vehicles, safety monitoring of heavy plant equipment, obstacle detection, surveillance applications and oceanographic surveying

Introduction.

The principal general requirements for a versatile industrial scanning millimetre radar system are:

- High resolution in both range and azimuth angular positioning.
- Robust construction for survival under high vibration conditions, (i.e. location close to large capacity diesel engines.)
- Operational in hostile environments; all weather operation with tolerance to dusty environments (building and mining sites) and resistance to impact damage from grit and stones.
- High reliability and Low maintenance.
- Immunity from adjacent sensors in a multi-sensor network system.
- Flexible software control to accommodate different applications and sites.
- System performance to conform to International EMC and safety standards.
- Production design amenable to medium and large-scale production.

A 77 GHz. FMCW radar with a scanning high gain antenna offers the high-resolution performance parameters. The maximum detectable range depends upon the system signal-to-noise, radar target cross- section, the radar processing system design and the maximum permissible equivalent isotropic radiated power allowable by international EMC standards and non-ionising radiation standards. Although MIMIC amplifiers are now available for the 76-77 GHz. band, the waveguide gunn oscillator power source offers a superior noise performance, [ref.1,8].

The requirements for a robust construction, hostile environment operation, adjacent sensor immunity and high reliability have been achieved by minimising the number of WR26 waveguide flanges and using the innovative design techniques developed from the Automotive Cruise-Control, (ACC), radar development programme [ref.1]. Prior to the development of consumer ACC radar systems, radar systems operating above 60 GHz. were limited to small and medium quantity production for military and a few commercial applications. Towards the mid 1990's, millimetre sub-components became available at reasonable costs from a wider variety of suppliers.

The principal building blocks of the scanning 77 GHz. FMCW radar system are illustrated in Figure 1. Figures 2 and 3 show the constructional details of the complete system and the sensor respectively.

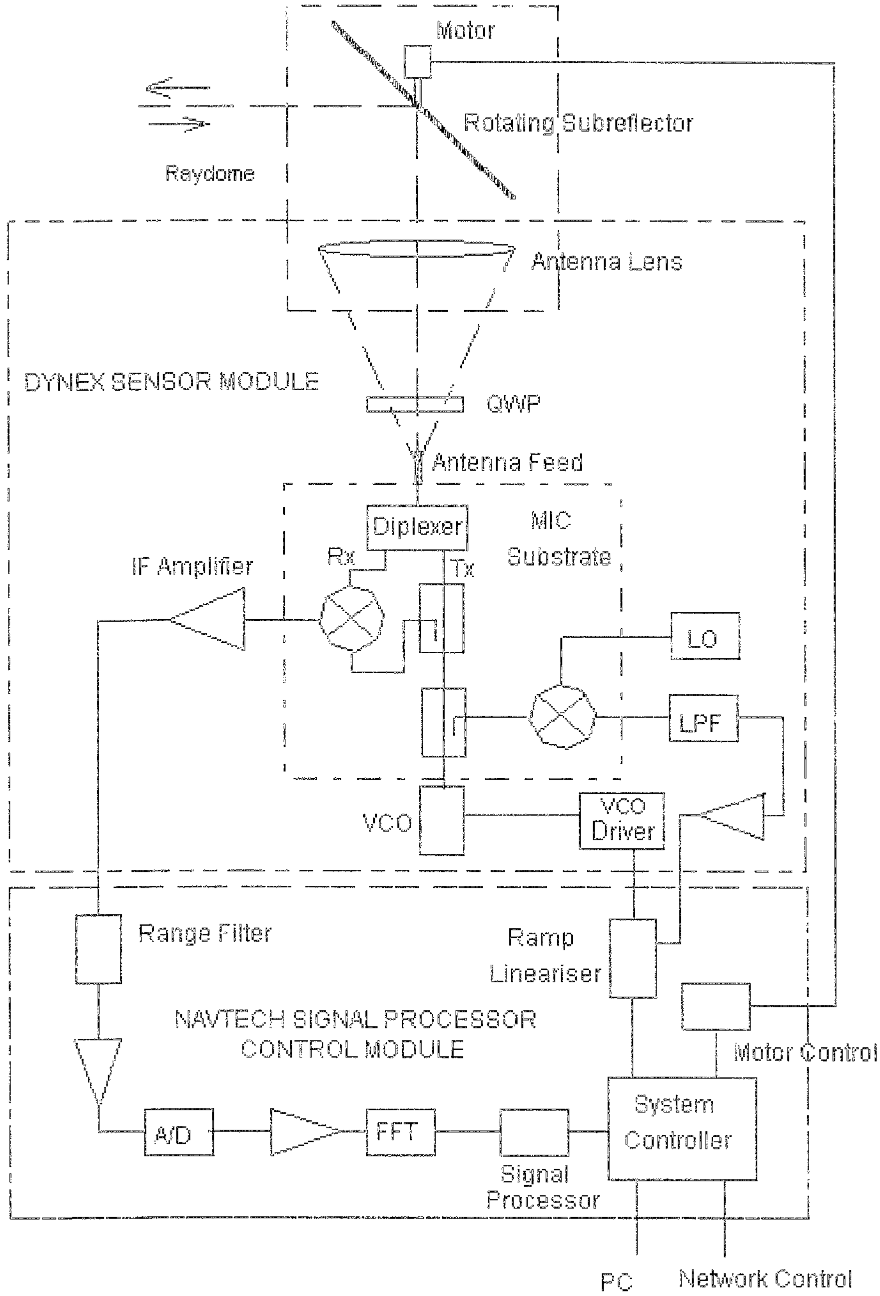

Figure 1. 77 GHZ SCANNING RADAR SYSTEM

[pnav.tcw]

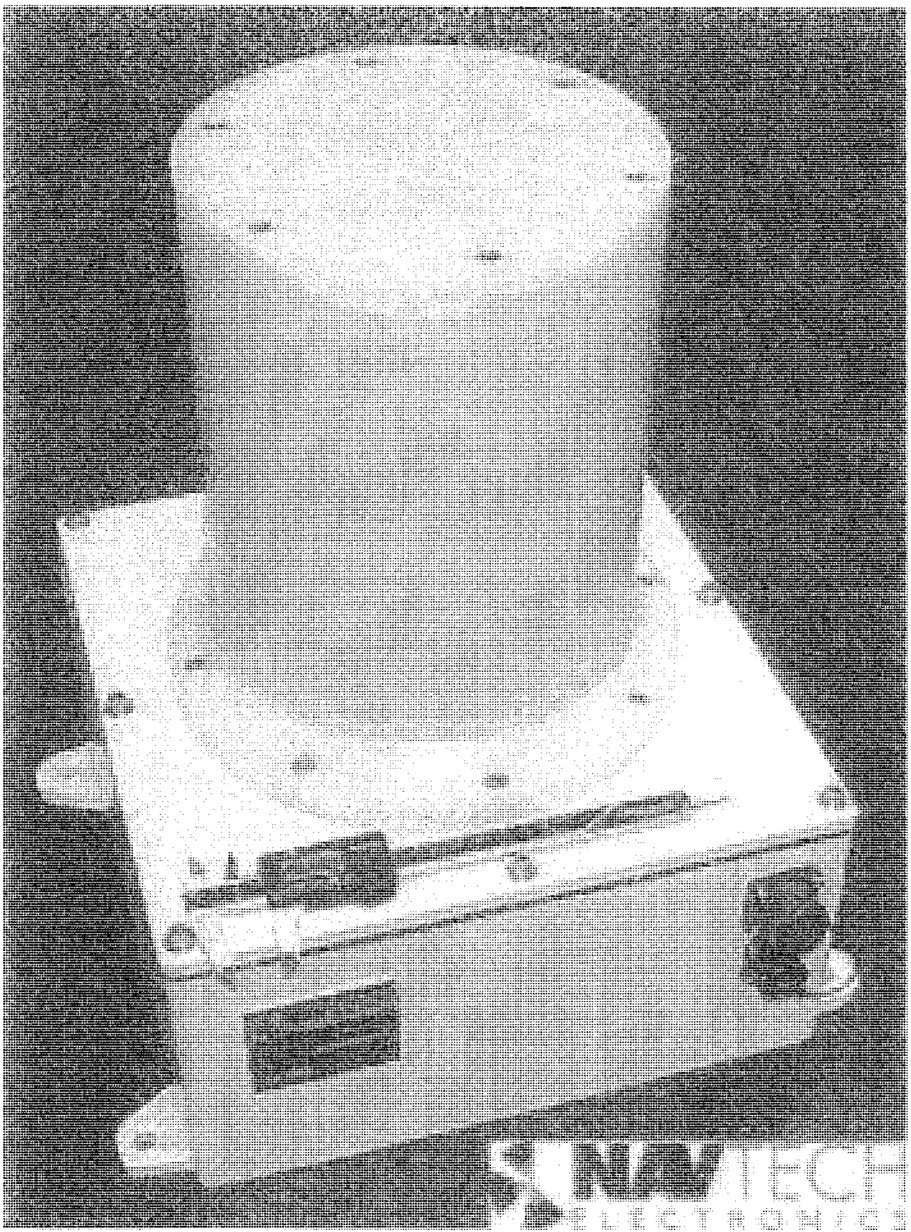

Figure 2. Complete Scanning Radar Assembly.

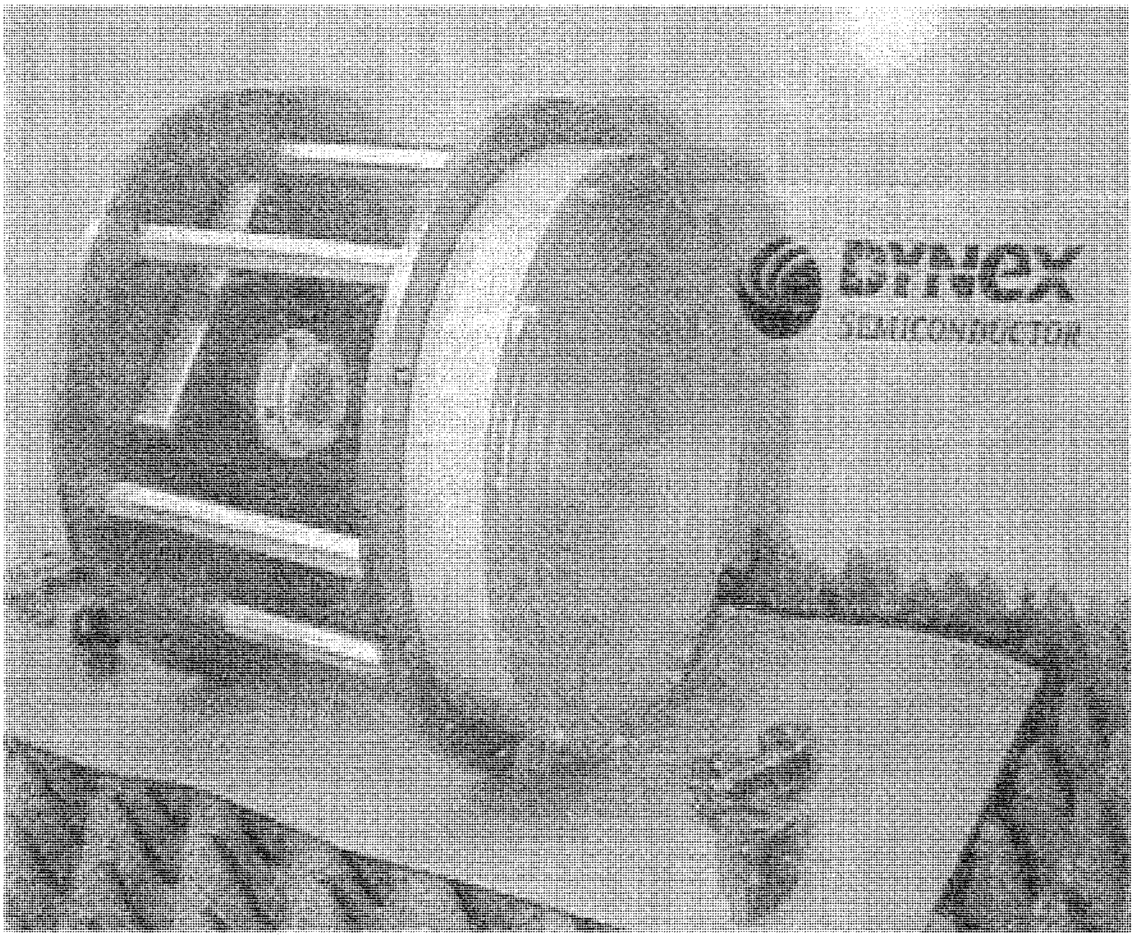

Figure 3. Radar Sensor Assembly module with Antenna Lens.
The waveguide Gunn oscillator is shown in foreground.

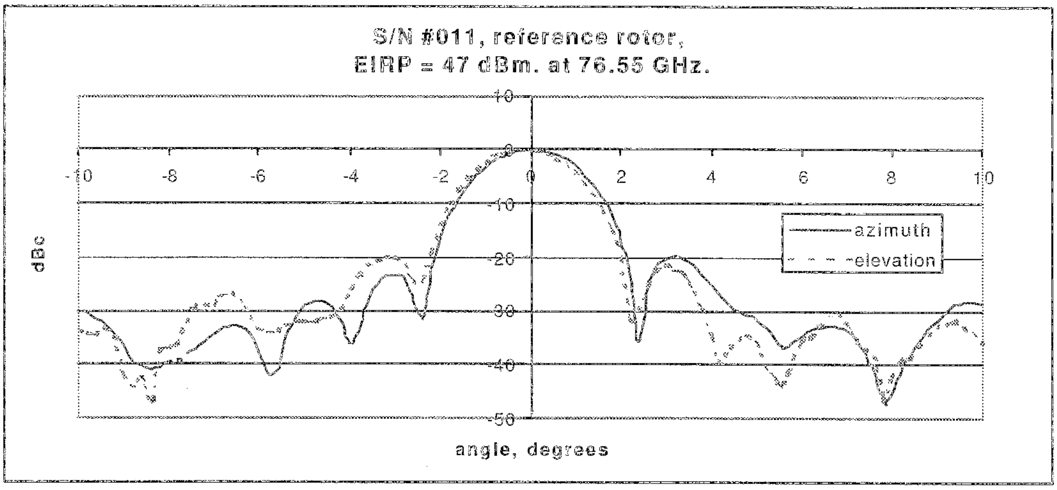

Figure 4(a). One-Way Sensor beamwidth plots with reference rotor sub-reflector.

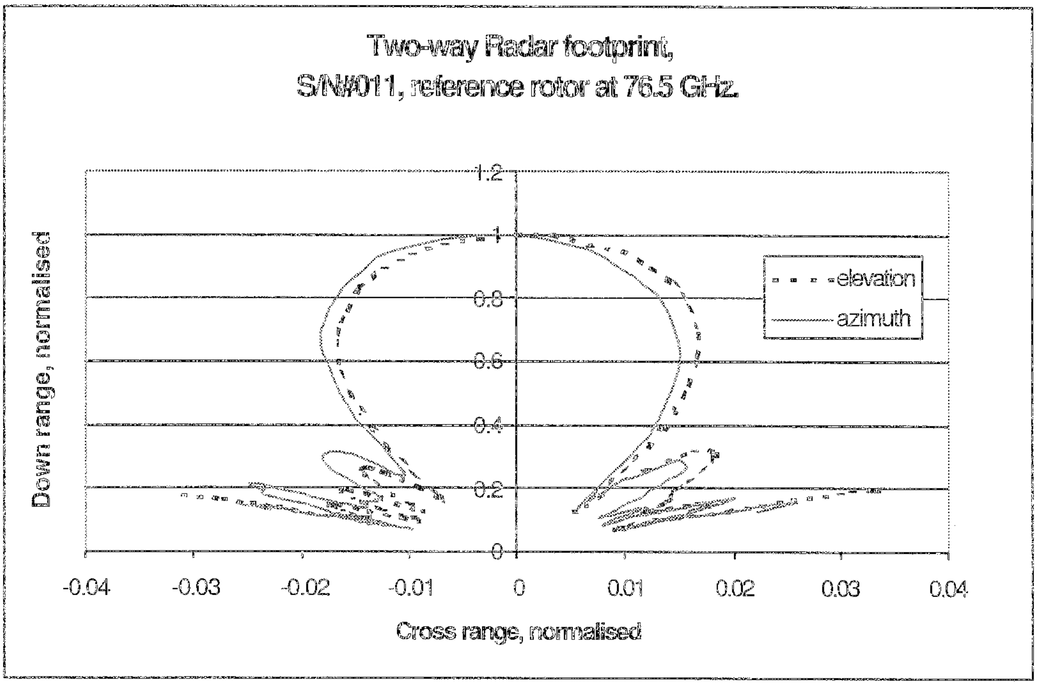

Figure 4(b). Sensor Two-way Radar footprints.

System Specification. [ref.3]

Transmit frequency range	76 to 77 GHz.
Transmit power	47 dBm. EIRP nominal
VCO bandwidth	< 600 MHz.
-3 dB. Beamwidth	1.8 degrees minimum azimuth and elevation, wider beamwidths options available.
Sweep time	1 mS default (other sweep times optional)
Max range	> 200m
Range accuracy	+/- 0.03 m.
Scanner azimuth resolution	0.09 degrees.
Scanner field of view	360 degrees
Scan speed	2.5 Hz. (other speeds optional)
Interfaces	CAN or RS232, (Ethernet and high speed serial option)
Supply voltage	+24 V nominal (18 - 36 V)
Size	321 x 321 x 438 mm.; complete assembly 321 x 321 x 171 mm.; sensor with antenna. 249 wide x 267 mm. high ; Optional Raydome and Scanner
Environment	IP66, NEMA-4X
Temperature	-20 to + 70 degrees C.
Vibration	6.8g , 5 - 200 Hz

Antenna Sub-Reflector Assembly.

Azimuthal angular coverage over 360 degrees is achieved from a synchronous spinning periscope sub-reflector positioned in the antenna aperture near field. The azimuth and elevation beamwidths and the elevation "tilt" angle can be independently adjusted by selecting from a range of sub-reflectors to suit individual site applications. Figures 4(a) and 4(b) show the antenna beamwidths and the corresponding two-way radar footprints of one of the sub-reflector configurations. A high impact resistant low-loss plastic is used for the weather-resistant raydome housing.

A high efficiency phase-retarded 160 mm. Fresnel lens produces an antenna gain of nominally 38.5 dBi. The corresponding transmission EIRP level, typically 47dBm., conforms to the permissible scanning fixed radar EIRP levels stipulated by the international EMC and safety standards.[ref. 4,5,6,7]. (The antenna characteristics of each production sensor module are measured both one-way and two-way in a computer-controlled anechoic chamber using a target simulator.) Phase retarded lens are relatively low cost, lightweight and are tolerant to the millimetre tanδ loss properties of the material. In medium quantity production this design can be fabricated by numerically controlled lathes; for larger quantity production, the shape is suited to lower cost injection moulding. Although conventional millimetre antenna lenses offer higher efficiencies, they are significantly heavier, require very low loss dielectric materials and are limited to higher cost fabrication techniques.

The monostatic antenna feed consists of a microstrip patch-polyrod configuration [ref. 7,8] which also functions as an ortho-mode transducer (OMT) for diplexing the Tx/Rx signals. A quasi-optic quarter wave plate, QWP, was chosen in preference to a microstrip 4-port hybrid to process the circularly polarised transmissions because of the wider VSWR bandwidth, lower loss and higher isolation bandwidth. Both the polyrod and the QWP shapes are suitable the low cost plastic fabrication techniques of injection moulding and extrusion.

Although the antenna feed is part of the antenna, the feed assembly has been integrated into the Tx/Rx assembly module. Figure 3 shows the construction details of mounting the antenna assembly to the Tx/Rx module. The gunn oscillator housing is shown in the foreground.

Tx/Rx Sensor Module.

With the exception of the waveguide gunn oscillator and the associated waveguide-to-MIC-transition, all the millimetre components are either surface mount elements or distributed elements and are located on a thin quartz MIC substrate. A schematic of the MIC assembly is shown in Figure 1.

The GaAs Gunn oscillator is a critical component to the 77 GHz. radar system and was developed during the ACC radar program. By using precision pressure die casting, the VCO cavity can be produced in volume at low cost; the associated high precision components within the cavity are produced using high-speed precision machine tools. The two most critical parameters of the VCO are the phase noise and the output power; a specification of the gunn oscillator is given in reference 8.

The VCO driver circuit, Local DRO oscillator, IF amplifier, mixer bias circuit, the loop filter/amplifier and the associated psu regulator circuitry are all fabricated on a single microwave pcb and may be assembled using pick-and-place automated assembly methods.

Signal Processor/Control Module.

The signal processing and control module includes all the sub-systems required to support the RF and sub-reflector assemblies.

VCO ramp generator: The frequency/drive voltage characteristics of the VCO are stored in non-volatile memory. On system start-up these are loaded into SRAM and then clocked into a precision DAC to drive the VCO. The sweep time of the VCO and swept bandwidth can be easily changed by altering the clock frequency of the DAC or the ramp tables respectively.

Lineariser: The ramp generator provides a good first attempt at producing a linear VCO sweep. To achieve higher linearity and to compensate for the effects of temperature or changing component characteristics, the system includes a closed loop lineariser. This uses the mixed product of the VCO and LO in a frequency discriminator. The output of the discriminator is compared with a reference frequency and the difference is fed back into to the VCO drive circuit. This closed loop component is then combined with the ramp generator output.

Power supplies: Several different supplies are required on board for both the analogue and digital electronics. To avoid excessive heat dissipation, these are provided by high frequency switch mode supplies. Careful board routing and filtering is required to prevent the noise from these appearing in the IF.

Self Test and Characterisation: An on board micro controller makes constant measurements of various reference voltages and signals throughout the board. In particular, the frequency characteristics of the discriminator are constantly monitored. Any deviation from the expected levels is reported to the supervisory software. A feature exists that enables the VCO to be characterised *in situ*. This means that the voltage/frequency characteristic of a VCO can be measured on first power up. There is no need therefore to spend time characterising each VCO with a spectrum analyser. This is achieved with a low cost PLL circuit

Intermediate Frequency Conditioning: Before the radar IF is sampled, a compensation is made for signal dispersion as it leaves the system and then again as it returns from the remote object. The standard filter has an R^4 characteristic although others can be configured. This means that the signal level prior to sampling will be constant for a particular radar cross section, independent of range. Additionally a high order anti-alias filter is used to prevent signal aliasing after processing.

Motor Control: The motor for the rotating sub-reflector is controlled on board and the rotation speed is programmable

Signal Processor: After signal conditioning the IF is sampled and the results stored in FIFO. This and in fact the majority of the system logic is implemented in a large programmable logic device (PLD). On board DSPs are then available to Fast-Fourier-Transform, (FFT), and perform power calculations. A single DSP is sufficient but a second is available for further parallel processing if required.

Communication: Basic low bandwidth communications are available from on board RS232 and CAN interface. Range and bearing to nearest obstacle are usually sent via these interfaces, however, at 1Mbit/s the CAN bus can be used to send the signal power in each range bin, albeit at low range and power resolution. This allows a remote image of the environment to be constructed. For higher bandwidth communications the data from the DSP is fed to an external board, which is still mounted within the same radar enclosure. Higher bandwidth Ethernet and USB are then available as required.

System Display Features.

During system development and testing a graphical user interface is available to display the imaged radar data in real time. An individual power spectra from a single polar axis can be plotted or a 360 degree polar plot created. In this format the different signal power levels are represented by a changing colour scale. Power in the scale is proportional to the radar cross section of the object measured.

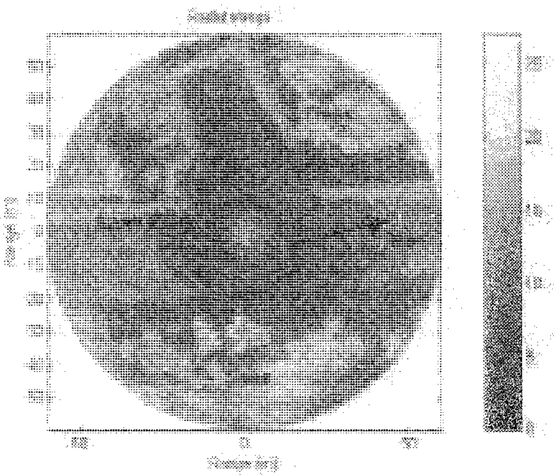

Figure 5(a) Polar Radar Display of road junction

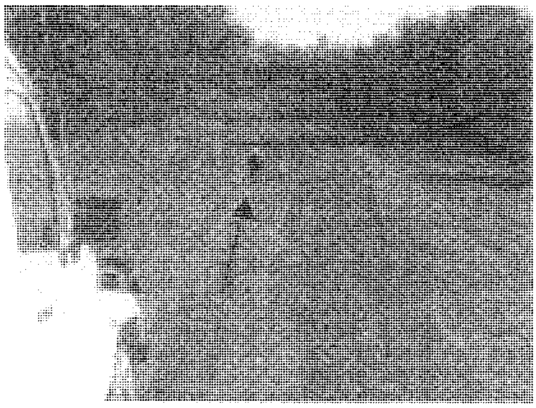

Figure 5(b) Photograph of road junction.

Applications.

The main target market for this radar system is as an industrial sensor. Units are currently used in the field for navigation of autonomously guided stevedoring cranes, Figure 6. These cranes move containers from the port quay to a holding yard. They are increasingly costly to man and after many years' research the first automated machines are being delivered. Scanning laser sensors have been used in indoor automation in the past to detect range and bearing to a number of fixed retro-reflective strips. These measurements are then combined with odometry measurements from the vehicle to provide a reliable continuous estimate of vehicle position.

In outdoor automation, however, the sensor must usually operate over greater distances and also be robust to fog, rain and dust. Operating at 77GHz., the radar is ideally suited for this purpose. The retro-reflective strips are replaced with simple Trihedral corner reflectors. The satellite based GPS is a competing technology in this market, however, this requires clear line of site to satellites at all times and a satellite constellation that is suitable for the high position accuracy required for reliable automation. Neither of these can be guaranteed, certainly in the port environment where the vehicle must collect containers from underneath the quay crane.

In another automation application the radar system has been used on the front of mining haul trucks. This is closer to the more usual obstacle detection application that the radar is being used for in the automotive market. This sensor system provides a far greater angular field of view however than is usually available from ACC automotive sensors. Further obstacle detection applications are being investigated in the railway industry.

With a high bandwidth communications interface all the radar data can be sent to a remote- processing platform. This makes it ideal as a development platform for radar detection. Applications investigated in these areas include security sensors and oceanographic survey instruments.

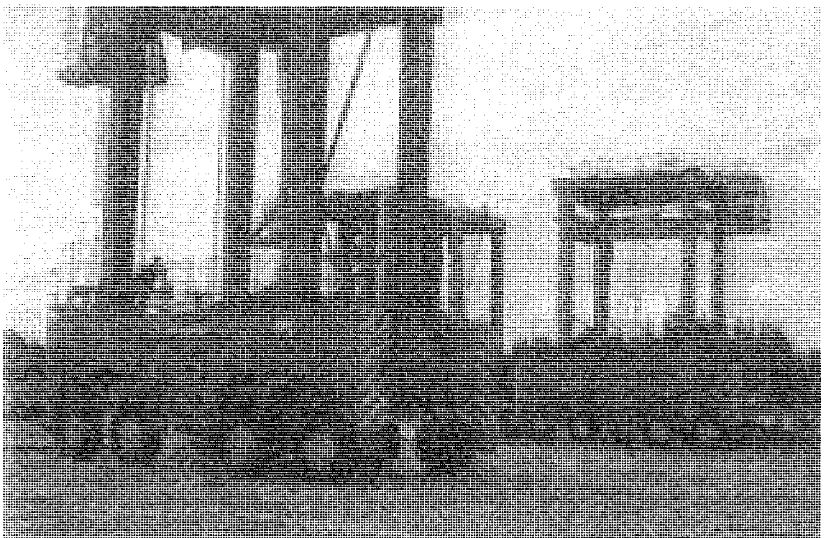

Figure 6. Stevedore cranes in port loading area.

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