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Millimetre Waves for Robotics

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Abstract

A review of the use of millimetre wave radar for robotic applications is presented. The paper includes a brief overview of the different radar and scanner technologies that are available and finishes with a review of some of the techniques that can be used to represent and use radar data.

1 Background

The term millimetre waves refers to that portion of the electromagnetic spectrum between 30 and 300 GHz, corresponding to wavelengths between 10 and 1mm. For robotic applications, most activity is concentrated around the atmospheric window at 94GHz [Seashore *et al*., 1979]. Since 77GHz was allocated for automotive radar, lower cost sensors at the lower frequency have begun to appear from Saab Tech [Eriksson and Broden, 1996] and Epsilon Lambda amongst others.

The resurgence of interest in millimetre waves arises from the realisation that there are limitations with what can be accomplished with infrared and optical systems, in particular their disadvantages in dust and fog or for nighttime viewing.

Niche commercial applications, particularly for industrial electronic distance measurement (EDM) and collision warning have been proposed since the early 1970's [Groll and Detlefsen, 1997], but it has only been in the last decade or so that the advantages of millimetre wave for autonomous guidance have been realised [Lange and Detlefsen, 1991].

One of the primary dual use vision and guidance applications has been the development of active and radiometric landing technology [Bui, 1991; Koester, 1992].

1.1 When to use Millimetre Wave Radar

For applications where the performance ultrasonic sensors is marginal either because the range is excessive or because the environment is too noisy or windy, scanning laser and millimetre wave radar sensors are the only viable alternatives. However, before a selection is made, a careful cost/performance analysis should be undertaken. In particular, if at least one of last four characteristics listed in Table.1 cannot be justified then it should not be used.

For robotic applications, particularly those involved with construction, mining or agricultural activities where dust is almost always present, or for long range outdoor activities that require an all-weather capability, millimetre wave is the frequency of choice.

Table.1 Sensor System Performance Comparison

Sensor Characteristic	Millimetre wave	Laser
Cost	Poor	Good
Tracking accuracy	Fair	Good
Classification	Fair	Good
Imaging	Fair	Good
Volume search	Fair	Poor
Adverse weather	Fair	Poor
Smoke, dust etc	Good	Poor
Dirty Antenna	Good	Poor

The all-weather capability is best described with the aid of the curves [Bhartia and Bahl, 1984] in Figure.1 that show atmospheric attenuation as a function of frequency.

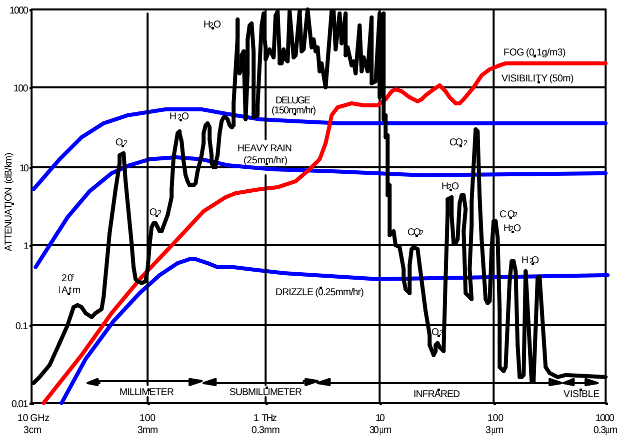

Figure.1 Atmospheric Attenuation Characteristics

When a comparison is made between the performance of a sensor at 94GHz ($\lambda \approx 3$mm) and a typical laser system ($\lambda \approx 900$nm), under clear conditions or in light drizzle neither suffer significant attenuation. However, as the rain rate increases, and the median drop size diameter increases into the optical region [Bogush, 1989], attenuation becomes significant for both (about 10dB/km at 25mm/hr).

It is the performance in mist and fog where the water drop diameter is such that the radar is operating in the Rayleigh region and the laser in the Mie (or resonant) region, that the largest differences can be seen. Under these conditions the radar attenuation is still insignificant, but the laser suffers an attenuation of around 300dB/km, which makes it all but blind.

A similar analysis can be performed for environments that contain smoke, dust, or even large concentrations of particles of biological origin (like pollen). These results [Brooker *et al.,* 2001] are summarised in Table.2.

Table.2 Attenuation due to Atmospheric Particulates

Source	**Matl**	r g/cm^3	e_r	**Diam. mm**	**Mass conc. g/m^3**	**Attenuation dB/km**	
						l**=4mm**	l**=0.9mm**
Dust: Winds	Quartz	2.6	2.25	1.E-02	10	2.20E-06	216.3
Stack: Stone Mill	Quartz	2.6	2.25	1.E-02	80	1.76E-05	1730.1
Stack: Steel Mill	Carbon	2	1000	1.E-02	10	3.28E-05	3230.6
Volcanic Dust	Quartz	2.6	2.25	2.E-03	5	8.80E-09	540.7
Pollen	Bio.	0.5	1.5	1.E-02	60	1.62E-05	1591.8

Safety Issues

Safety guidelines for sources of non-ionising radiation are based on the rate at which electromagnetic radiation is absorbed in the body. This is expressed as the specific absorption rate (SAR), i.e., the rate of microwave energy absorption per unit mass.

For microwave exposed workers, a safety factor of approximately 10 is incorporated into the guidelines with reference to the scientific-consensus threshold for adverse health effects.

The following are considered when exposure levels are considered:

- Occupancy of areas
- Duration of exposure including on/off times, beam direction, duty factors and sweep times etc.
- Part of body exposed
- Uniformity of exposure field

The maximum exposure limit that covers the millimetre wave band (15GHz to 150GHz) ranges from 50W/m^2 for microwave exposed workers down to 10W/m^2 for the general public.

A typical millimetre wave radar developed for visualisation applications will radiate a power of 10mW from an antenna aperture of 250mm.

In the near field $R<0.5D^2/\lambda$ ($R<8$m for $\lambda=4$mm), the maximum power density within the beam can be conservatively estimated as:

$$W_m = \frac{4P_T}{A} \quad \text{W/m}^2$$

where W_m – Maximum power density (W/m^2)
P_T – Net power delivered to the antenna (W)
A – Physical aperture area of the antenna (m^2)

For the radar, the peak power density equates to 0.2W/m^2. This is a factor of 50 less than the maximum continuous exposure limit for the general public, and a factor of 250 less than the maximum exposure limit to a microwave worker.

In general, any exposure that occurs will be in the far field where the power density is given by:

$$W = \frac{P_T G}{4pr^2} \quad \text{W/m}^2$$

where G – Antenna gain with respect to Isotropic
r – Distance from the antenna

For a gain of 4375 (36.4dB at 77GHz), and 10mW transmitter power, the power density reduces to:

$$W = \frac{3.48}{r^2}$$

Table.3 Power Density in the Far Field

Range (m)	**Power Density (W/m$^{2)}$**	**Safety Margin (public)**
10	0.0348	287
20	0.0087	1149
50	0.0014	7184
100	0.00348	28735
200	0.00009	114942

If the beam direction and scanning as well as the on time are all taken into account, the amount of radiation exposure from a millimetre wave radar becomes totally insignificant.

2 Millimetre Wave Radar Principles

Radar systems operate by radiating electromagnetic radiation, and receiving an echo return. The angular resolution is determined by the antenna beamwidth and the range resolution by the bandwidth of the transmitted signal. Resolution is defined as the minimum separation between two point reflectors of equal size that can be distinguished by the radar after processing. In angles, this is approximately 0.85 of the antenna 3dB beamwidth [Skolnik, 1970], while in range it is proportional to the reciprocal of the transmitted bandwidth $dR = c/2\Delta f$.

2.1 Range Resolution

Because the propagation of electromagnetic radiation is faster by a factor of 10^6 than that of sound through the air, to achieve the same range resolution with a radar system, its electronics must operate a million times faster than that of a sonar system. A real pulse with a duration $\tau = 1$ns is required to obtain a resolution of about 15cm. Because it is difficult to produce very high peak powers using solid state amplifiers and because a pulse time-bandwidth product $B\tau \approx 1$ is required for matched filtering of the received echo, operational range of such systems is very short.

Alternative methods of obtaining high resolution have been developed in the last fifty years. They include pulse compression, FM and stepped frequency techniques. In essence these techniques widen the transmitter bandwidth and lengthen the effective pulse width to improve the resolution while still offering good range performance.

In environments where multiple radar sensors are in use, the modulation type or operational frequency must be selected with care to ensure that mutual interference between sensors does not occur. Pseudo Noise (PN) is the modulation of choice in this case [Groll and Detlefsen, 1997].

2.1.1 Pulse Compression

In a pulse compression system [Bogush, 1989] such as that shown in Figure.2, a very brief pulse consisting of a range of frequencies passes through a dispersive delay line (SAW expander) in which its components are delayed in proportion to their frequency. In the process the pulse is stretched; for example a 1ns pulse may be lengthened by a factor of 1000 to a duration of 1µs before it is up-converted, amplified and transmitted.

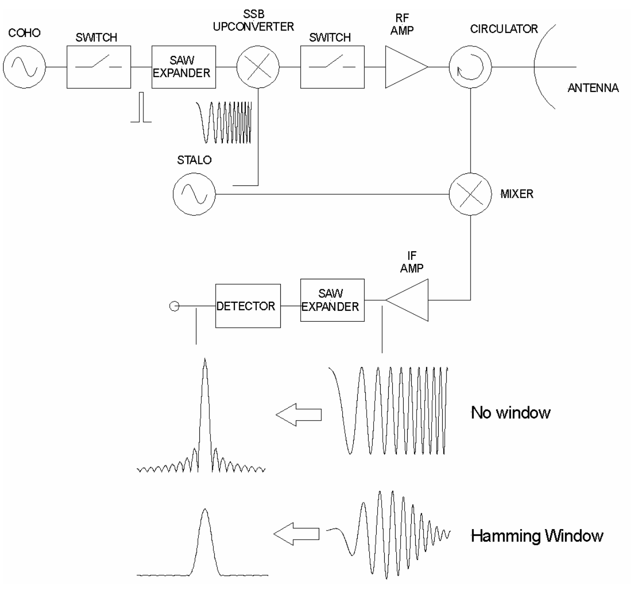

Figure.2 Pulse Compression Radar

The echo returns from the target are down converted and amplified before being fed into a pulse compression network that retards the echo by amounts that vary inversely with frequency to reduce the signal to its original 1ns length. The compressed echo yields nearly all of the information that would have been available had the unaltered 1ns pulse been transmitted. A slight sacrifice in range resolution (≈1.3) is the penalty incurred in reducing the range sidelobes from –13.2dB with no weighting to about –43dB with Hamming weighting [Kirsten, 1979].

The amount of signal-to-noise ratio (SNR) gain achieved is approximately equivalent to the pulse time-bandwidth product $B\tau$. Though using surface acoustic wave (SAW) technology to implement the pulse expansion and compression functions limits the maximum $B\tau$ product to about 1000 [Skolnik, 1970], it is in common use today because it is both compact and robust.

Pulse compression technology is not suitable for short-range robotic applications because the minimum range is determined by the time taken to transmit the stretched pulse, which in the example above equates to 150m.

2.1.2 Stepped Frequency

When using a real or compressed pulse waveform to achieve high range resolution, there is a challenge to receive the acquired data at the required rate (or bandwidth). For 0.15m resolution, both the real pulse and pulse compression systems would have to sample and process data at a peak rate of at least 1GHz for a period of time equivalent to the range extent of the area of interest.

A technique that avoids the data acquisition problems associated with the real pulse mode is the pulse-to-pulse stepped frequency mode. A pulsewidth τ is selected to span the range of interest, for example a 100ns pulse will span a range of 15m. The frequency of each pulse is shifted by a small amount ΔF from that of the previous pulse, where ΔF is selected to be about $1/2\tau$ = 5MHz to ensure that there is no phase ambiguity in the returned signals.

After each pulse is transmitted, the received echo at a particular range is coherently detected (to maintain the phase information), and the amplitude and phase information stored. For transmit frequency F_1, the phase of the received echo will be:

$$\Phi_1 = \frac{4pF_1R}{c}$$

For a static target, the phase of the next pulse echo transmitted a frequency of F_2 will be Φ_2. For a sequence of pulses equally spaced in frequency, there is a predictable pulse to pulse phase shift of $\delta\Phi$ that is a function of the frequency difference $\Delta F = F_2 - F_1$.

$$d\Phi = \frac{4pR\Delta F}{c}$$

This pulse-to-pulse phase shift appears as an apparent Doppler frequency, which is a function of the range to the target. If multiple targets appear in the same range bin, then each will produce a unique frequency that can be extracted from the time domain signal using the Fast Fourier transform (FFT) process.

The total unambiguous range after processing is $c/2\Delta F$, and the range resolution is $c/2F_{tot}$ where F_{tot} is the total frequency excursion of the transmitted signal. For a sequence of N pulses $F_{tot} = N\Delta F$. For an ultimate resolution of 15cm F_{tot} = 1GHz, ΔF = 5MHz and N = 200 samples. As with the pulse compression case, a Hamming window will increase this resolution by a factor of 1.3 to 19.5cm.

In a robotic environment, the primary disadvantage of this technique is that it takes time to perform a single measurement. For example, if the maximum operational range was 300m, as each new pulse can only be transmitted after the previous pulse has returned, the pulse repetition interval (PRI) is at least 2µs with a 1µs settling time, making the total time required to perform a measurement at least 600µs for N=200.

A total of twenty 15m bins is required to span the range from 0m to 300m and each of them will have to be processed by the FFT to produce range bins. If 256 point complex FFT's are used, then the total processing time required would be 20x256xln(256) ≈ 28400 time units.

A further difficulty that must be considered is that if the target is mounted on a moving vehicle, then Doppler effects will shift the apparent range of the targets.

2.1.3 Frequency Modulated Continuous Wave

FMCW radars operate by transmitting a linear frequency chirp Δf of long duration T_d. At any time, the echo signal received is shifted in frequency from the transmitted signal by the product of the roundtrip time T_p to the target and the rate of change of frequency $\delta f/\delta t$. If the received signal is mixed with a portion of the transmitted signal and filtered, the resulting output will be a constant beat frequency f_b.

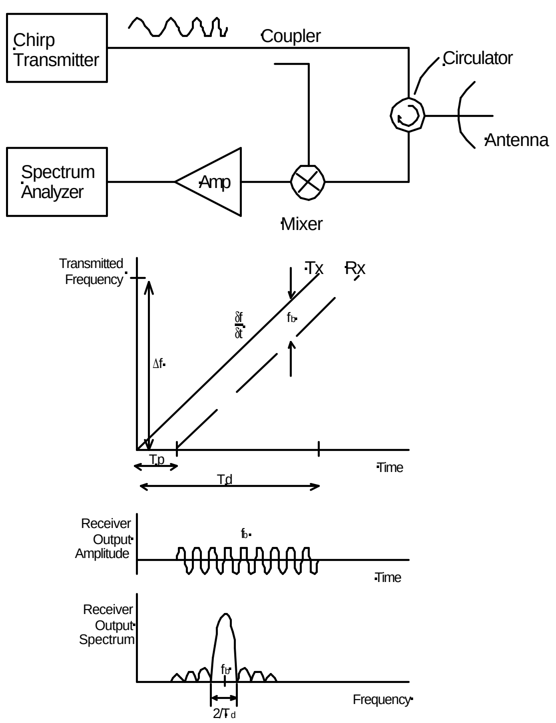

Figure.3 FMCW Radar

Two factors limit the range resolution of these systems, the first is a function of the chirp bandwidth Δf, and the second is the actual linearity that can is achieved for the transmitted chirp.

An exceptionally high-resolution radar system may have a chirp bandwidth Δf=1GHz and a sweep time of 2ms. The theoretical range resolution that can be achieved if only the chirp bandwidth considered is:

$$dR_{chirp} = \frac{c}{2\Delta f} = \frac{3\times10^8}{2\times10^9} = 0.15m$$

For a rate of change of frequency (chirp slope) $S=\delta f/\delta t$ at any point on the graph, the linearity Lin is defined below:

$$Lin = \frac{S_{\max} - S_{\min}}{S_{\min}}$$

The resolution that can be achieved is the product of the linearity and the range to the target, so for a target range of 300m and a linearity of 0.001, the resolution is 0.3m.

The two results are generally combined in quadrature to determine the ultimate system range resolution:

$$dR = \sqrt{dR_{chirp}^2 + dR_{lin}^2} = 0.335\,m$$

The beat frequency for a radar with the characteristics defined above, and a target range of 300m is the product of the round trip time to the target and the chirp slope:

$$f_b = T_p \frac{df}{dt} \approx T_p \frac{\Delta f}{T_d} = \frac{2R}{c}\frac{\Delta f}{T_d} = 10^6 Hz$$

The relationship between the measured beat frequency and the range is:

$$\frac{R}{f_b} = \frac{T_d c}{2\Delta f} = 0.0003\,m/Hz$$

As many targets can be present in the beam, spectrum analysis must be used to extract all of the frequencies generated in the received signal. This function is usually implemented in software using the Fast Fourier Transform (FFT) process.

If the signal is observed for a time T_d = 2ms then the width of the FFT frequency bin W = 1/T_d = 500Hz (15cm) and main lobe width, shown in Figure.3, is twice that. The 3dB bandwidth of the filter produced by the FFT process is 0.89 bins (13.3cm) for no windowing, increasing to 1.3 bins (19.5cm) for a Hamming window [Currie and Brown, 1987].

To produce a spectrum spanning the whole range from 0m to 300m with a bin size of 15cm requires 2000 bins. These can be produced by a complex 2048-point FFT making the total processing time, 2048.ln(2048) ≈ 15600 time units, about half as long as the time taken for the stepped frequency processing.

2.2 Angular Resolution and Antennas

Angular resolution is determined by the antenna beamwidth that is in turn governed by the antenna aperture and the transmitter frequency. The relationship between the antenna diameter (D) and the beamwidth is:

$$q_{3dB} = \frac{70\,l}{D} \text{ deg}$$

Millimetre wave radar is used for robotic applications where size and mass are constrained, because a narrower beam can be obtained from a given aperture at high frequencies than at low frequencies. Even at 94GHz, however, a trade-off must be made between antenna size and acceptable beamwidth. Generally apertures of 150 to 250mm are used, which, at 94GHz equate to a beamwidth of between 1.5° and 0.9°.

Most radar systems operate in the far-field where the radiated power density is governed by the inverse-square law and the beamwidth in degrees remains constant. At close range, the pattern and power density are range dependent. The border is generally defined at a range:

$$R_{ff} > \frac{D^2}{l}$$

As a first approximation, it can be assumed that the beam diameter equals the antenna aperture in the near field region and only starts to diverge in the far field.

In addition to beamwidth requirements, antenna gain is important for longer range operation. Gain is determined from the aperture area (A), the aperture efficiency (η) and the wavelength (λ) as follows:

$$G = \frac{4phA}{l^2}$$

Efficiencies from 0.5 to 0.7 are generally achieved except where ultra low sidelobes are required in which case the efficiency is generally lower due to under illumination of the lens or reflector.

A final factor that is important is the antenna impedance match. This determines how much of the transmitter power is reflected back into the radar and how much is radiated (or absorbed). Because FMCW radars often transmit and receive simultaneously through the same antenna, it is critically important to have a good match, otherwise reflected power can saturate the sensitive receiver circuitry.

Most antennas used for outdoor robotic applications are hermetically sealed horn-lens types rather than the more conventional Cassegrain designs as the former offer all-weather operation. In addition they are more robust and because there is no aperture blockage, their sidelobe levels are generally also lower.

3 Scanning and Imaging

3.1 Mechanical Scanning

For most robotic applications, a real beam is scanned by physically rotating the antenna using a pan/tilt mechanism or by utilizing the reflective properties of a finely polished rotating mirror.

All mechanical radar scanning systems need to have angular resolution capabilities exceeding that of the radar system for which they are constructed, so that the radar system's designed capabilities are not compromised by the scanning system.

Scanning systems using a rotating antenna have the advantage that they can be more compact than mirror scanners as there is no separation between the antenna and the scanning mirror. They also do not suffer from angular resolution diminution due to unintended relative movement between the antenna and mirror. However a scanning mechanism required to rotate the radar antenna and electronics will require heavier and more powerful drive components, slowing scan times and making the spatial resolution demands of the radar system more difficult to meet as well as significantly increasing the system's power requirements. Communication of electrical signals between rotating and non-rotating parts of a rotating antenna radar increases the complexity and reduces the reliability of such a system.

A scanning mirror radar allows the inertia of the systems rotating parts to be minimised. This makes quicker scan times in both axes possible while minimising scanner drive power requirements and making spatial resolution requirements easier to achieve. With appropriate design the need to pass any electrical signals between rotating and non-rotating parts can be eliminated reducing complexity and removing any associated electrical noise. Suitable mirrors are generally constructed from aluminium with its good reflectance properties across millimetre wavelengths and weight advantages. For larger applications composite aluminium mirrors provide low mirror mass while maintaining the required mirror stiffness.

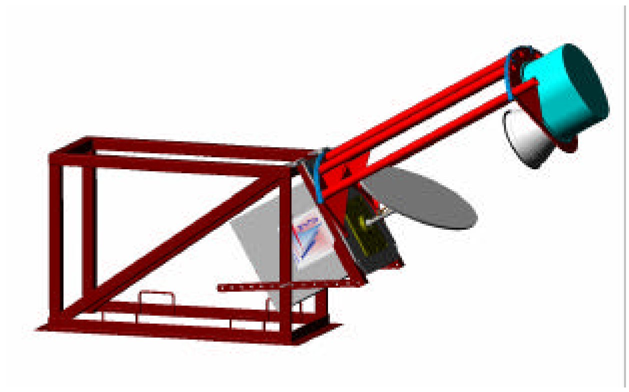

Figure.4 Mirror Scanner

3.2 Electronic Scanning

Because of reliability issues relating to mechanically scanned systems, a number of research institutes are investigating electronically scanned options. Electronic scanning using phased array technology at low frequencies is a mature technology and is described in a number of texts [Brookner, 1985]. Phased array antennas produce a narrow beam by transmitting from a large number of small (wide beamwidth) antennas simultaneously. To scan the beam, a progressive phase shift is introduced into each of the radiating elements. At millimetre wave frequencies, high losses and expense limit their application at this stage, though advances in micro electro-mechanical systems (MEMS) technology is a showing promise as a technology that can produce low loss, low cost phase shifters [Barker and Rebeiz, 1998].

3.3 Image Representation

Two-dimensional images made at low grazing angles such as those produced by airborne radar systems are generally displayed on a Cartesian or polar grid with each pixel encoded with the reflectivity of the ground at that point. The images produced are similar to aerial photographs taken from directly overhead with the sun illuminating the terrain from the radars position. The use of a Cartesian grid allows the integration of multiple scans onto the grid by averaging the amplitudes of successive returns [Brooker, 1998]. This technique reduces the effect of speckle (interference from multiple scatterers in a single range bin) and works particularly well if the radar is moving.

The following characteristics have been observed in radar images made at 94GHz:

- Smooth horizontal surfaces (water, roads and runways) are specular and reflect most of the power away so they appear dark.
- The far edges of roads and runways appear brighter than the surrounding region due to corner effects.
- Grass and cultivated fields scatter fairly uniformly and show texture.
- Isolated scrub and trees are good scatters and generally appear brighter than grass and crops.
- Large trees, banks and buildings cast deep shadows.
- Buildings and other manmade objects are specular reflectors because their surfaces are flat and smooth.
- The reflectivity of natural surfaces increases with grazing angle so steeper hills appear brighter.

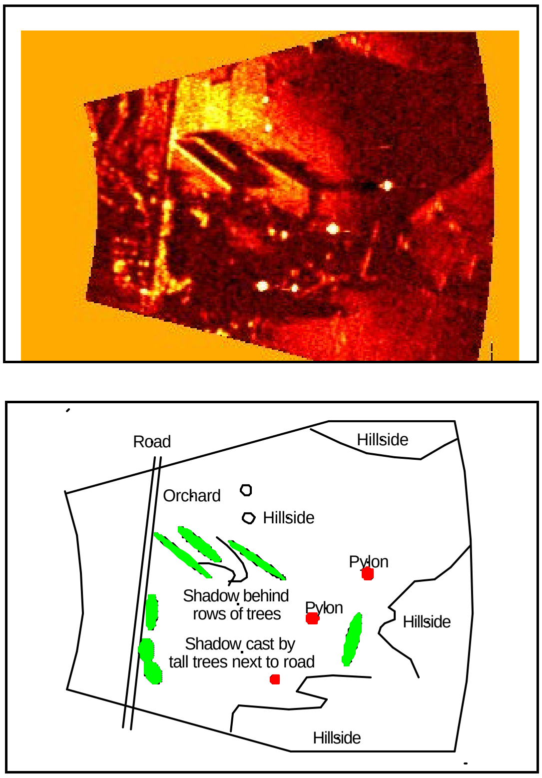

Figure.5 Real Aperture Millimetre wave Image

For navigation or guidance purposes images like these can be correlated with aerial photographs or specific features can be extracted from the image and associated with similar features extracted from a photograph. The feature association technique is faster than correlation because only a few features are required, but it requires some skill to examine an aerial photograph and predict those features that are likely to be visible on a radar image

Where scenes contain height and reflectivity data, a representation similar to that used by scanning laser systems called the IHS (intensity-hue-saturation) can be used. In this representation height determines the colour (hue) and the brightness (intensity) is derived from the reflectivity.

For short-range navigation and obstacle avoidance applications in buildings or underground, various representations have been tried. A volume cell with only two states (full or empty) is used in [Lange and Detlefsen, 1991] to indicate the presence of a target. Most systems now use statistical representations that allocate a target presence probability to each cell. The evidence or occupancy grid method [Martin and Moravec, 1996; Elfes, 1989] is one of the most widely used representations for several reasons; they are easy to implement, have fixed memory and computational requirements and they allow a statistical representation of the environment (albeit at spatially discrete intervals). More recently, other probabilistic methods such as particle filters [Leal *et al.*, 2000; Fox *et al.*, 2000] and sums of Gaussians [Majumder *et al.*, 2000] have been used that allow probabilistic mapping in a non-spatially discrete way.

An alternative to probabilistic mapping is the use of feature primitives. This is where a set of primitives (edge, corner, wall, building, etc.) are defined, extracted from the sensor data and located in Cartesian space. This method suffers from the fact that primitives can be very difficult to extract, and may be ambiguous. Combinations of the various representations are possible.

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