System Solutions using MMW sensors

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***Abstract* — MMW technology has historically been used for high spec military applications but the lower costs and increased accessibility of this technology enable it to be more widely applied. Roke Manor Research has extensive experience in using this technology and two specific case studies will be presented to illustrate the approach of providing system solutions using MMW technology. These are based upon the Pandora™ System and the Miniature Radar Altimeter (MRA). Theses represent two different approaches one being a customer driven requirement and one being a technology driven solution.**

I. INTRODUCTION

Millimetrewave sensor technology is considered a technology of the future and a number of major applications have tried to leverage this technology to achieve wide market penetration. However the technology has never really made that major commercial breakthrough that many have expected. One major benefit that this technology has seen however is the continued investment in developing the solutions and techniques and devices that provide the basis for wider commercial exploitation. We have seen that imaging at 93GHz, radar (such as Automotive radar @24GHz and 77GHz) and radiometry @ >20GHz are proven technology solutions waiting for that major commercial breakthrough.

At Roke Manor we have provided many sensor system solutions using millimetrewave technology and what is presented in this paper are two forms of solution for two very different problems firstly the Pandora™ system which is focused on detecting people in “curtain sided” lorries and secondly the Miniature Radar Altimeter (MRA) used for height monitoring and applied primarily to UAV’s and VTOL aircraft (Unmanned Air Vehicles, and Vertical Take Off and Landing).
This paper will present the application and requirement, the technology and its applicability to the problem, the challenges and implementation issues and finally the results for each system. The paper concludes by reviewing the future requirements for developing millimeter wave systems, and has some observations which may be necessary to enhance the commercial success of these systems.

II. THE PANDORA™ SYSTEM

The customer (HMG’s Home Office Immigration and Nationality Directorate) directed that the system had to be capable of imaging through curtain sided and plastic-sided vehicles. Their reasoning being that these types comprise the majority of UK-bound freight vehicles. Curtain sided vehicles as opposed to metal sided or container-carrying vehicles are also particularly vulnerable to forced entry with only the aid of a sharp knife and a length of tape to re-join the damaged curtain once the clandestines were onboard. Our customer also insisted upon a passive rather than an active detection method to avoid any possible legal challenge from either the lorry drivers or their illegal passengers about health hazards caused by irradiation from RF sources.

Previous experience gained using the prototype HOPE system at the French channel port of Calais showed that clandestines could often be inventive in concealing themselves opportunistically in suitable containers found in the load. In one such case five illegal immigrants used the load of plastic rubbish (wheely) bins to conceal themselves. The relatively low millimeter wave frequency used by both HOPE and Pandora™ systems for detection, and the better penetration afforded at that frequency, allowed our trials operator to identify the anomalies in the load, and the vehicle was subsequently stopped and searched.

It was these key customer requirements that have driven the design of the Pandora™ system optimizing the performance to differentiate human sized and shaped anomalies within the scene of interest.

The full range of the customers requirements were:

- alien detection system solution
- imaging inside of curtain sided vehicles
- passive system
- accommodate large vehicles
- 20mph vehicle speed
- permanent installation in sea port environment, all weather
- 24/7 coverage
- remote database
- intelligent GUI
- vehicle identification / correlation
- real-time

A. The Physics Behind the Technique

All objects emit electromagnetic radiation proportional to the physical characteristics of the object and its absolute temperature. Similarly, subject to the physical characteristics of the object they also allow the transmission of radiation through them. The amount of energy transmitted will be dependant upon the frequency of the incident radiation and this forms the emitted radiation detected by the Pandora™ PMMW systems.

In simplistic terms there are three classes of ideal object. These classes of object are described below and illustrated in Figure 1.

1) Consider an object that is emissive. The noise temperature of the radiation that is emitted from the object, T_e, is proportional to the object's emissivity, ε, and its temperature T.

   $T_e = \varepsilon T$

   For a perfect black body the emissivity would be equal to unity but real objects generally have emissivities less than unity.

2) Alternatively an object can reflect the energy incident upon it. The noise temperature of the radiation reflected from such an object, T_r, will be proportional to the object's reflectivity, ρ, and the noise temperature of the incident radiation T_{ref}.

   $T_r = \rho T_{ref}$

   A good example of this would be the hot exhaust of a vehicle. At the frequencies that the Roke Manor Research systems currently operate the metal of the exhaust appears purely reflective and will appear at the temperature of the surrounding scene.

3) Consider an object that is transmissive. A transmissive object allows a proportion of the radiation incident upon it to pass through whilst absorbing the remainder, or alternatively the radiation passing through the object is attenuated. Such an object will transmit energy proportional to the objects transmissivity, τ, and the incident radiation's noise temperature T_{trans}.

   $T_t = \tau T_{trans}$

However, as is generally the case, most real objects exhibit all of the properties described above to some degree, though one property will generally dominate. Therefore, the total noise temperature of an object, T_0, can be seen to be:-

$$T_0 = \varepsilon T + \rho T_{ref} + \tau T_{trans}$$

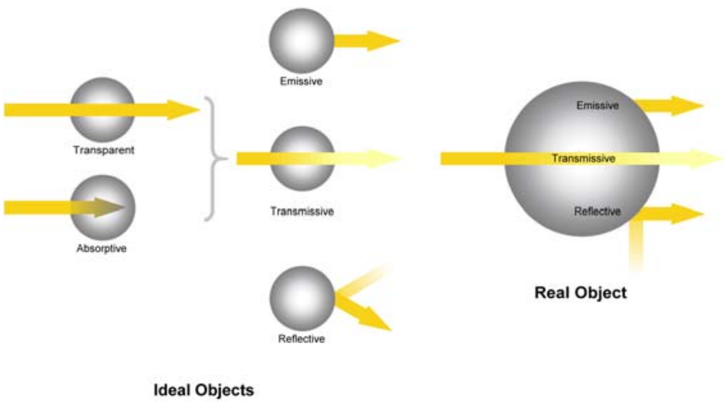

Figure 1 : Ideal and Real Objects

It should also be noted that the coefficients of emissivity, reflectivity and transmissivity are also frequency dependant. An image obtained from a passive millimetric system will therefore appear different when viewed using different frequencies.

B. The System in Outline

As has been shown the basic principles of radiometric imaging are relatively simple. A detector is used to receive radiation from the scene under consideration. The output from this detector comprises a value proportional to the received power level. This detector can then either be scanned to build up an image or it is possible to use an array of sensors to produce a similar image. Both solutions have advantages and disadvantages and it is the task of the system designer to choose the optimum solution for the task at hand. Typically, the scanning solution is less robust than an array solution due to the significant numbers of constantly moving mechanical parts and the reliance on a single detector. The array solution, though more robust, requires multiple detectors that can have significant cost implications.

The Roke Manor Research systems employ an array of low cost detectors operating at a single frequency. The cost of the detectors is kept low through the extensive use of commercial off the shelf (COTS) components. This ensures that the system is both robust and cost effective.

Similarly, the system's resolution has been optimised for the task it was designed for :- the detection of people within soft sided vehicles. The objects of interest, people, are sufficiently large to allow the implementation of a relatively low resolution system. This has again allowed us to take advantage of COTS components for the construction of the system. Here the design decision was taken to implement a relatively low resolution system that ensured detection of people-shaped anomalies but ignored the fine detail within the image. Again, choosing a lower resolution meant that we were able to operate at lower frequencies. This proved advantageous due to the improved load penetration of RF radiation in the system's operational frequency band.

C. The Pandora System: Implementation

Figure 2 : Pandora™ System

"Pandora™" is also an acronym : **P**assive **A**pparatus **N**otifying **D**etection **O**f **R**adiating **A**liens.

Our customer's requirements were that the system should be robustly designed and suitably finished for permanent installation in a seaport environment. It should accommodate the largest size of vehicle permitted under European Union (EU) traffic regulations. In particular, vehicle drivers must be able to travel through the scanner without slowing down or in any other way modifying their behaviour; the imaging system process was to be effectively 'transparent' to them. The Pandora system was subsequently trialled at 20mph, a typical seaport speed limit, and produces an identical quality of image to that obtained at 2mph. Experience gained with the prototype indicated that a 'standard background' was desirable since this gives rise to a greater contrast of the internal structure and contents of the load. Further reflectors mounted on the top of the steelwork prevent the sun shining directly into the detector boxes and reducing image contrast. The system also offers a UPS to condition the electrical power, with seamless transition to an automatically-started standby generator in case of a mains supply failure, a remotely-interrogated database to hold details of each and every vehicle transit, automatic number plate recognition and an air conditioned operator cabin for 24/7 operation in relative comfort. In addition, some form of 'image size normalization' was to occur to ensure that vehicles were scaled to fit the viewing screen, so for example a road train and a Luton van would both be scaled to fit onto the same size of screen display area.

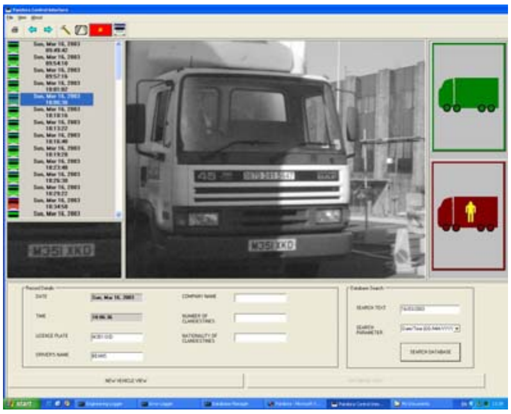

Figure 3 : Pandora™ system GUI

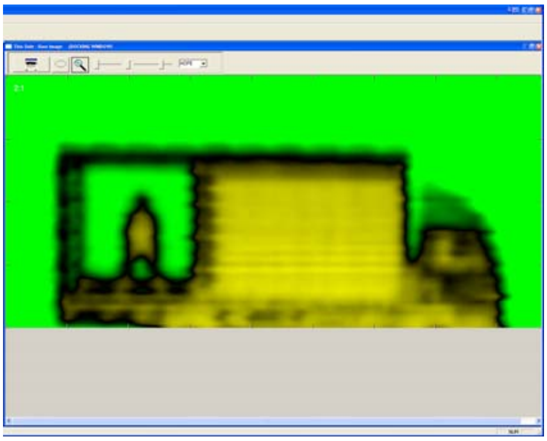

Figure 4 : Image of Clandestine in van

When a suspicious vehicle is viewed by the operator, he places a 'rubber-banded' ellipse around any suspicious region, and touches the red icon on the touch sensitive screen which shows a lorry with a person, as opposed to the green lorry icon when vehicles are deemed to be 'clean'. The images of suspicious vehicles are automatically transmitted from the control cabin via a fibre optic link to a remote 'Search station' where enforcement personnel stop the vehicle and search it, aided by the image as to the location in the load where possible clandestines may be found.

Whilst the image processing is active, other systems are scanning the entry roadway, identifying the number plates of approaching vehicles and extracting these for the database. Over twenty national formats can currently be handled and the success rate is very high once the recognizer is fully trained. A separate system comprising infra red beam breakers across the road, and a camera system which views the side of the vehicle, tracks up to 150 features such as corners, marks and rope eyelets that are used to accurately determine the speed of the vehicle as it passes through the system to provide image normalization prior to displaying the image to the operator.

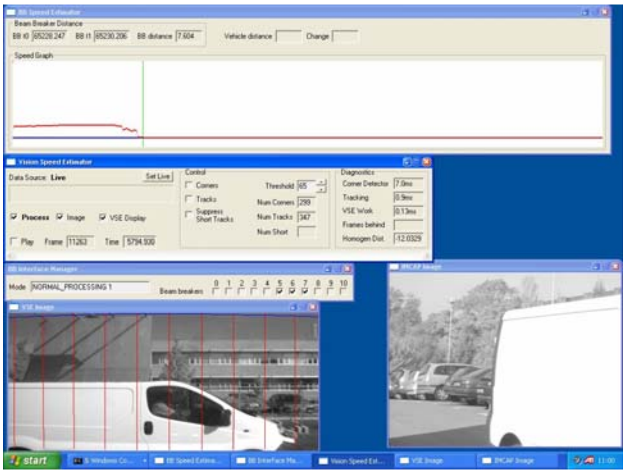

Figure 5 : Vision Speed Estimator

Since the Pandora™ system relies on the operator's ability to recognise anomalies in the load, the front end display system allows the operator to choose their preferred display presentation from a number of 'palettes' of colour combinations, or a monochrome grey scale. It is also possible to vary contrast and temperature window ranges directly on the screen by means of slider and other operator image display controls to enhance areas where the content is uncertain. Although the images appear less human-like initially, the eye/brain combination has evolved over countless millennia to recognise the basic human form and operators soon develop a remarkable intuitive sense for what is 'normal', quickly spotting anomalous shapes in the small percentage of transiting vehicles which contain people, even in large, complex, mixed loads.

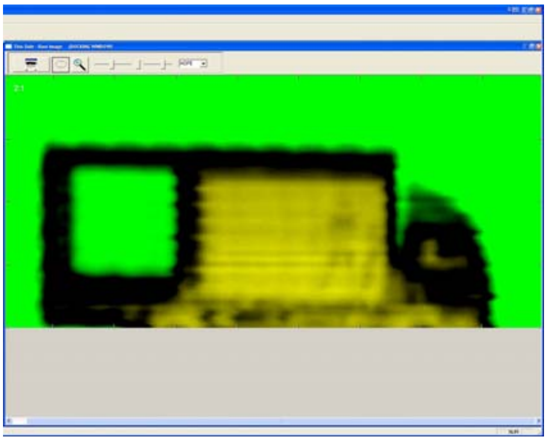

Figure 6 : Operator variation of contrast to identify two persons on the front of the load

III. MINATURE RADAR ALTIMETER : MRA

The Minature Radar Altimeter product from Roke Manor provides an alternative application for millimeter wave technology. The driver here was initially the fact that the millimetre wave technology enabled a radar to be designed. Here the portfolio of products is complemented by the introduction of a high frequency unit targeted for different applications than the lower frequency units. A proposal for the development of a millimetre wave based system was made on the basis of a perceived customer requirement as defined below.

A. Customer Requirements

The following list contains the key customer requirements for the MRA.

- Internal Customer was Roke Private Venture Fund
- Required Altimeter Accuracy <0.05m
- Operational range approx 100m
- Unit cost low
- Easy to interface to
- Robust, suitable for harsh environments
- Target market UAV's, VTOL, hence low RCS etc

In order to meet these customer requirements a pragmatic approach was taken based upon known autoradar technology. This could provide low NRE from technology re-use, provide robust packaging based upon the same experience from autoradar environment, a frequency of operation compatible with the technological requirements. There were however some unknown issues that would only be proven by realization and these relate to whether the range and accuracy requirements could be met within the system architecture limits defined by the recovery and dwell time constraints and also whether there were any Doppler issues

B. Technical Solution : Frequency Modulated Continuous Wave (FMCW)

By adopting the FMCW architecture a number of design issues are simplified. At millimetre wave frequencies pulse shaping is difficult and if implemented would not be a low cost solution. For the ranges of up to 100m the path loss does not require high transmit powers and therefore receiver saturation and recovery times are not as significant and system gain can be implemented straight forwardly.

C. FMCW: A Primer

For those unfamiliar with FMCW concept the key system is provided in the following figures. The transmit waveform is "chirped" that is the frequency is ramped linearly with time (it is often a repetitive saw tooth ramp to provide an increasing and decreasing frequency the advantage of which will be clear later). The transmit signal is then amplified and sent via the transmit antenna to the target and the return signal is received and mixed in a homodyne fashion with the transmit signal. However the chirp ensures that the transmit frequency has now changed and so the resulting tone is indicative of the electrical return path to the target.

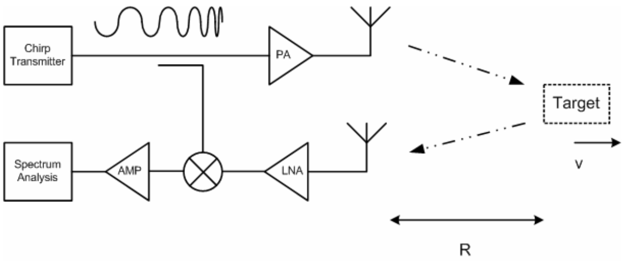

Figure 7 : FMCW Block Diagram

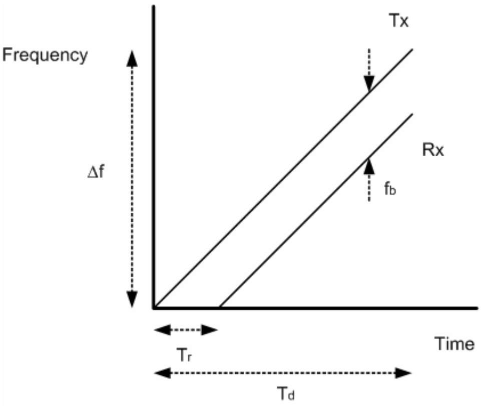

Figure 8 : Beat frequency and time plot of TX and RX signals

c	-	speed of light
T_r	-	round trip to target
R	-	distance to target
f_b	-	beat frequency
δR	-	range resolution
δf_b	-	spectral resolution
T_d	-	dwell time
v	-	target velocity

Figure 9 : Key for equations

$$f_b = \frac{\delta f}{\delta t}.T_r = \frac{\delta f}{\delta t}.\frac{2R}{c}$$

$$\delta f_b = \frac{\delta f}{\delta t}.\frac{2\delta R}{c}$$

$$T_d = \frac{c}{2\delta R}.\frac{\delta t}{\delta f}$$

$$R = \frac{f_b\, c}{2}.\frac{\delta t}{\delta f} = \frac{f_b\, c}{2}.\frac{T_d}{\Delta f}$$

Figure 10 : FMCW equations

For targets that are moving away from the radar the perceived frequency of the return signal is lower than would have been expected for a static target so an uncertainty is introduced and this is sometimes represented on a range-Doppler plot. To overcome the uncertainty introduced by the Doppler from a target an average of the beat frequency is taken for an upward sweep and then a downward sweep. The Doppler frequency can be determined by half the difference of the up and down sweeps.

D. MRA The Implementation

The present approach used for the MRA is a single millimetre wave board, a baseband processing board and a robust mechanical housing containing the lens antenna system for the radar.

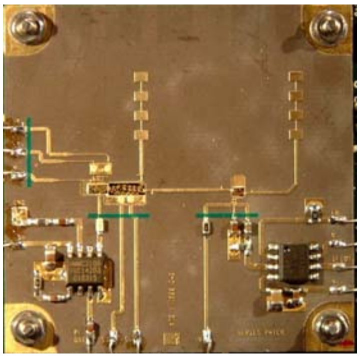

Figure 11 : Millimetre wave board

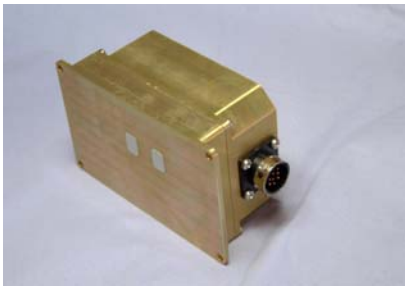

Figure 12 : Complete MRA

The use of digital signal processing (DSP) to do the "clever stuff" enables the high frequency board to be relatively simple and hence reduce cost. The DSP engine provides the control, interfacing and calculations necessary to provide the correct information on the target. However the optimization of the parameters available is not easy for example to improve range accuracy it is necessary to increase the dwell time, however for moving objects the amount that the target has moved in the time it takes to determine how far the object is away may be critical.

IV. CONCLUSIONS

In this paper two very different system solutions using millimetre wave technology have been presented. In common parlance both “do what they say on the tin”, both are proven systems operating and meeting the customer requirements. Both also use complementary technology necessary to produce a system.

However both these systems use millimetre wave technology developed for another purpose in these cases LMDS, Autoradar and Military technology. For both of these systems the necessary technology could not have been developed for these on an individual basis.

Which leads to the inevitable conclusion that technology re-use is a critical part of this market sector and that it is necessary to identify which markets will provide technology development in the future.

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