UWB TIME DOMAIN RADAR SYSTEMS

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Abstract

Detection of buried ordnance and landmines has proved to be a successful application of UWB radar technology, which, after some years of research and development has now reached maturity in terms of production. This paper will review the technology that has been implemented in production systems and describe some current research and development into hand-held and vehicle based radar systems. The paper will also highlight the future engineering challenges to achieve not only detection but recognition and identification using UWB radar.

Introduction

Landmine detection using electromagnetic induction (EMI) techniques is well established and a range of metal detectors is commercially available. Recent developments using dual sensor technology combining EMI and ground penetrating radar (GPR) have enabled improved discrimination against metal fragments to be demonstrated in live minefields and reductions of up to 7:1 compared with the standard metal detector have been achieved in the field by hand-held systems such as MINEHOUND™. Such systems can be considered to be at the highest levels of technology readiness.

Scattering of electromagnetic energy from a landmine results from the impedance differences of the landmine compared with the host material. Canonical targets such as cylinders, which are similar to landmines, have well understood free space scattering characteristics that will be modified by the dielectric of the soil. The mine may have a number of scattering centres, each with their own angular radiation pattern and, in the case of plastic landmines; the internal structure of the mine may generate additional scatterers. Most plastic landmines may be considered as multiple layered dielectric cylinders, of which each interface causes a reflection, the impact of the small internal metallic fuse being minimal.

Technical requirements

Most GPRs for landmine detection operate in a region where the wavelengths radiated are greater than, or in the same order of magnitude, as the dimensions of the landmine. This is between the Rayleigh and Mie (or resonance) region of the landmine dimensions and is quite unlike conventional radar systems where the target dimensions are generally much larger than the wavelength of the incident radiation, i.e. the optical region.

GPR is generally operated so that the antenna is very close to the ground surface and target such that the energy transfer is predominantly either induction or quasi-stationary (the near field). Some workers have reported detection by means of evanescent wave propagation. Stand-off GPR systems can be operated such that the energy transfer is in the far field region and this in turn brings challenges of energy transfer and above ground clutter rejection. The total path losses within a few wavelengths may be as much as 100dB depending on the material and as GPR systems do not have a total loop gain much in excess of 120dB the designer has a major challenge to detect landmines signatures within very short ranges of typically 20ns[1].

Free space radar systems need only consider propagation phenomena through the atmosphere but waves propagating through natural media experience attenuation of both the electric (E) or magnetic (H) fields. This causes attenuation of the original electromagnetic wave. The graph in Figure 1 shows the two-way attenuation loss in dB per 10cm plotted against frequency for a material with a relative dielectric constant of 9 and loss tangents of 0.1 to 0.5 respectively. Clearly as the centre frequency is increased from 1GHz to 5GHz, the attenuation loss for a soil with a loss tangent of 0.2 has increased from 10dB to over 50dB.

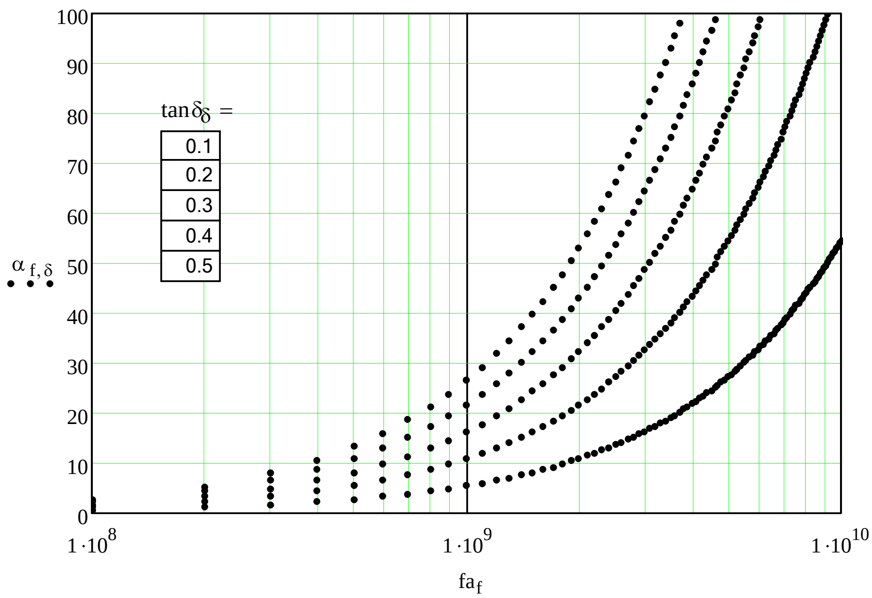

Figure 1 Material losses in dB per 10cm plotted against frequency in Hz for values tan δ from 0.1 to 0.5

The impact of material attenuation on signal characteristics can be seen from the following simulation. A Ricker wavelet is the second differential of a Gaussian impulse and is typical of the radiated impulse from a GPR. Transmitting this through a lossy material is equivalent to passing through a low pass filter with a slope in this example of 15dB per octave, which corresponds to a loss tangent of 0.3. The resulting effect on the time domain signal and the spectrum is shown in Figure 2 and Figure 3. The larger wavelet is the transmitted waveform and the lower the received. Further examination of the received waveform shows it is extended in time by 30%.

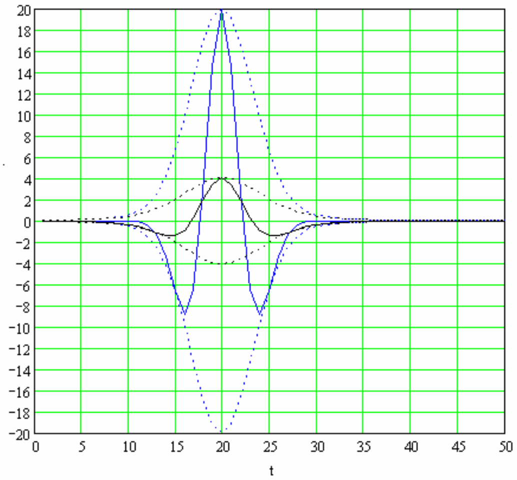

Figure 2 Effect of lossy ground on pulse amplitude and shape.

The effect on the spectrum is shown in Figure 3 which shows the peak of the spectrum shifted to lower frequencies and the higher frequencies considerably reduced.

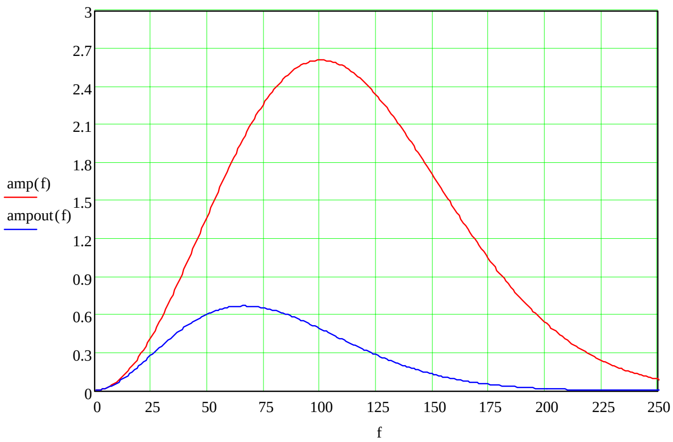

Figure 3 Spectrum of transmitted and received signals after passing through lossy ground

A major difficulty for operation of GPR systems is the presence of clutter within or on the surface of the material or in the side and back lobes of the antenna. Clutter is defined as sources of unwanted reflections that occur within the effective bandwidth and search window of the radar and present as spatially coherent reflectors. Animal burrows, cracks in the ground are examples of features that will cause reflections. Careful definition and understanding are critically important in selecting and operating the best system and processing algorithms. Clutter can completely obscure the buried target and a proper understanding of its source and impact on the radar is essential. A key issue is the effect on the radar of variations in the topography of the ground surface caused by pothole or ruts. Methods of processing the radar signals that adjust the delay time to the front surface to “flatten it” will actually distort the radar signature of buried targets. Abrupt discontinuities can also cause multiple reflections, which become superimposed on later arriving reflected energy. Such 'interference' will be extremely difficult to remove.

The range resolution of GPR is generally set by the bandwidth of the received signal. When a number of features may be present, a signal having a larger bandwidth is required to be able to distinguish between the various targets and to show the detailed structure of a target. In this context it is the bandwidth of the received signal which is important, rather than that of the transmitted wavelet. The soil acts a low pass filter, which modifies the transmitted spectrum in accordance with the electrical properties of the propagating medium. There are some applications of GPR, such as road layer thickness measurement, where the feature of interest is a single interface. Under such circumstances, it is possible to determine the depth sufficiently accurately by measuring the elapsed time between the leading edge of the received wavelet provided the propagation velocity is accurately known. Although a greater depth resolution is achieved in wetter materials for a given transmitted bandwidth because of the reduced wavelength in high dielectric materials, earth materials with significant water content tend to have higher attenuation properties. This characteristic reduces the effective bandwidth, tending to balance out the change so that within certain bounds the resolution is approximately independent of loss within the propagating material. Where interfaces are spaced more closely than one half wavelength the reflected signal from one interface will become difficult to resolve with that from another. It should be noted that the normal radar criteria for range resolution is less appropriate for the case of a weak target adjacent to strong target and there is no accepted definition of resolution for the case of unequal size targets.

The plan resolution is defined by the characteristics of the antenna and the signal processing employed. In general, radar systems (apart from SAR), require a high gain antenna to achieve an acceptable plan resolution. This necessitates a sufficiently large aperture at the lowest frequency to be transmitted. To achieve small antenna dimensions and high gain therefore requires the use of a high carrier frequency, which may not penetrate the material to sufficient depth. When selecting equipment for a particular application it is necessary to compromise between plan resolution, size of antenna, the scope for signal processing and the ability to penetrate the material. Plan resolution improves as attenuation increases, provided that there is sufficient signal to discriminate under the prevailing clutter conditions.

Hand-Held UWB time domain radar

MINEHOUND™ is an advanced, dual sensor, mine detector comprising a Ground Penetrating Radar (GPR) developed by ERA Technology Ltd (UK) and a Metal Detector (MD) based on the VMH3 manufactured by Vallon GmbH (FRG).

The GPR electronics [2] is comprised of two main sections; these are the RF and the digital sections as shown in Figure 4, the RF section is responsible for signal conditioning and down conversion, whilst the digital section is responsible for signal processing, control functions and the generation of the audio output. These two sections are placed side-by-side on a single six layer PCB with a very high component count and component density.

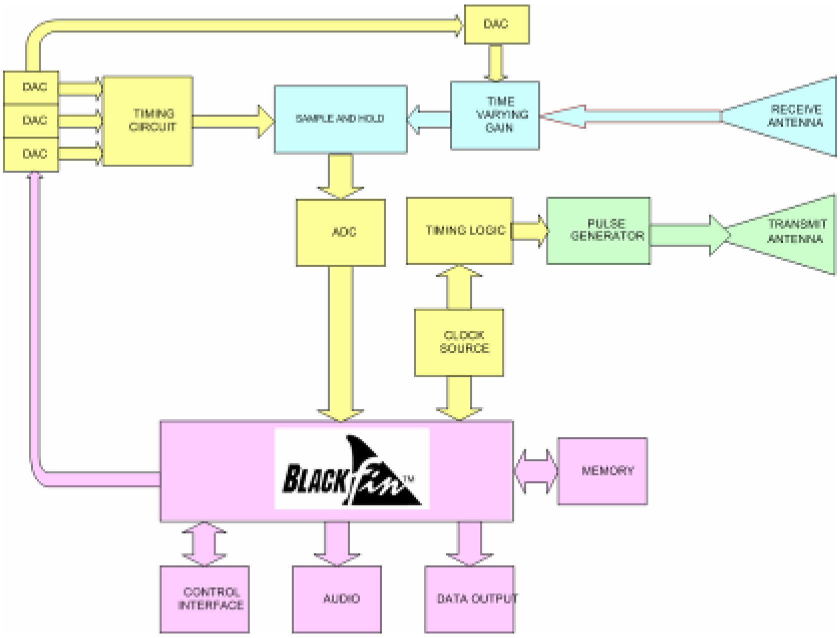

Figure 4 Minehound radar module system diagram

The RF section is responsible for signal conditioning and down conversion, whilst the digital section is responsible for signal processing, control functions and the generation of the audio output. These two sections are placed side by side on a an extended single Eurocard (220mm by 100mm) six layer PCB, shown in Figure 5. The UWB radar generates 240ps duration, 12V impulses every 1us using an integrated step recovery diode pulse generator and transmits these via an UWB antenna with a centre frequency of 1GHz, operating from 200MHz to 2GHz thus radiating 1ns duration wavelets. The UWB receiver applies a time varying gain profile to the incoming signal before sampling every 50ps.

The RF section applies a time varying gain profile to the incoming signal before sampling. The signal is then down converted to base band using an interleaved sampling technique, this down converted signal is then digitised and the waveform is reconstructed using an averaging process. The waveform-sampling window is 19.2ns and this waveform is reconstructed over a period of 16.4 ms which results in an A-scan refresh rate of 61Hz.

Figure 5 Radar transmitter receiver and processor

Sampling is carried out by sequentially incrementing the sample time position each pulse repetition interval up to 512 samples and then repeating the process. For example, a sampling increment of 50 ps is added to the previous pulse repetition sampling interval to enable sampling of the received signal at regular intervals. Using a digitally generated slow ramp and analogue generated fast ramp to create the sequence generates the incrementally timed samples. These samples are then down converted to a slower time frame using interleaving and an averaging process. The key RF component block is the wide bandwidth Schottky diode sampling system developed by Cobham.

In the radar, a total of 512 samples are gathered. After amplitude and time drift correction the centre 256 samples are actually used for subsequent signal processing. Note that the ramp derived time sampling is not the main contribution to timing drift. Averaging of the signal, necessary to improve the signal to noise ratio, is carried out by sampling a fixed number of times at each incremental point. The digital section receives the radar signal from an ADC, which results in a sustained serial data rate of 14Mbit per second. The on-board DMA controller deals with this data and the samples are placed in L1 memory on the Blackfin™. The signal processing module then operates on this data and produces the audio stream. The audio data is then moved under DMA control to a DAC, which reconstructs the audio waveform.

The digital section receives the radar signal from an ADC, which results in a sustained serial data rate of 14Mbit per second. This data is dealt with by the on-board DMA controller and the samples are placed in L1 memory on the Blackfin™ [3]. The signal processing module then operates on this data and produces the audio stream. The audio data is then moved under DMA control to a DAC, which reconstructs the audio waveform.

In parallel with this process, the Blackfin™ is responsible for dealing with control functions typically fulfilled by a micro controller. The Blackfin™ core has been designed with control and DSP functions in mind and, as such, is ideally suited to this application. There are a number of configuration changes which need to take place at the 32us averaging rate; this results in a 14 bit parallel, 14Mbit per second data rate, which again, is dealt with by the DMA controller. Another part of the control task is implementing the drift compensation technique. This ensures that drift in the start point of the sampling window, which is due to thermal changes affecting component tolerances, is removed before the data is passed to the signal-processing algorithm.

The Blackfin™ is ideally suited to the radar application for a number of reasons. It is rare to find a DMA controller on this class of DSP and, without the DMA controller, the peripheral data rates could not be reliably sustained while running a background control task. The peripheral set on the Blackfin™ is well featured and meets the needs of the application whilst maintaining headroom for implementing future functionality. The Blackfin™ system interrupt controller fully supports all the on-board peripherals and allows for a flexible interrupt driven system design to be implemented. The Blackfin™ core contains dual multiply accumulate units which allow the optimised signal processing to be dealt with efficiently. The DSP core clock is capable of running at 400MHz; however, the Blackfin™ dynamic power management functions allow the clock to be tailored to a lower speed to conserve power. The on-board core controlled core voltage generator allows the core voltage to be lowered to the level which is required to maintain the desired core speed. Significant power savings and extended battery life are the rewards for lower core speed and core voltage. The radar consumes 2.3W and contains all the processing needed to identify a landmine.

Vehicle radar systems

The multi-channel radar system described in this paper consists of 16-channel radar as shown in Figure 6 and Figure 7. Each radar channel operates as a self-contained module and is triggered by an interface board, which ensures that each pulse is transmitted in its own pre-assigned time slot. The data from each radar module is concatenated and fed by a USB interface to a laptop computer.

Figure 6 COBHAM 16 channel radar system

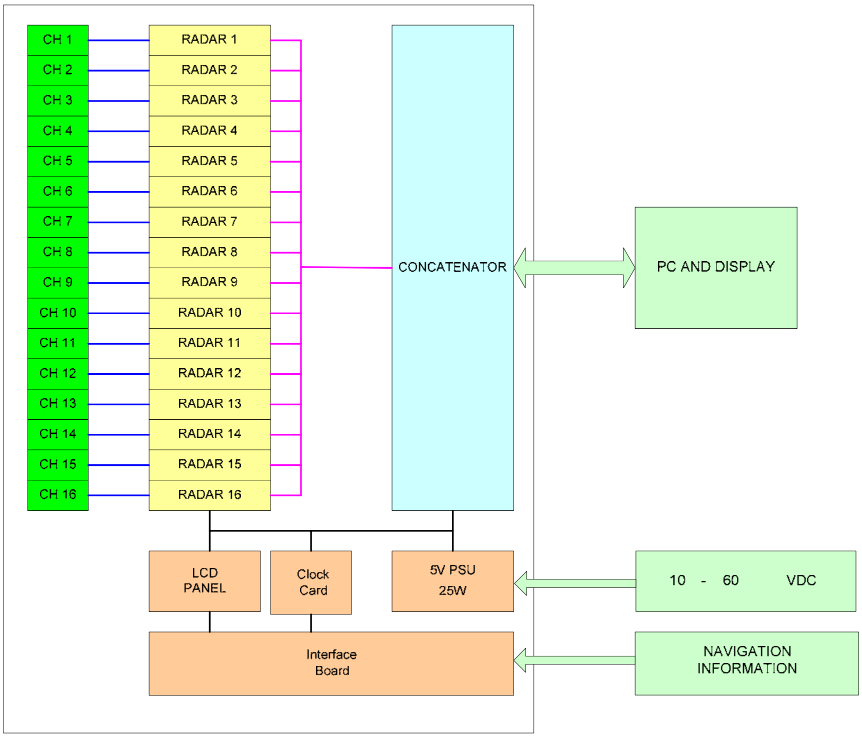

Figure 7 System diagram of multi-channel radar

The pulse repetition interval of one microsecond and the sampling window of 25ns of each module define the timing of the radar boards. This enables a theoretical maximum of 40 time slots, but practically a maximum 32 time slots is available, allowing for a guard band around each. The radar can be constructed to provide any number of channels up to this value and the current development is a 16-channel system, which offers a swathe width of 2.6m at the current antenna element spacing.

The obvious differences between hand-held and vehicle radar systems are the speed of survey and the difference between the types of survey, with the vehicle being a “one shot” survey of the ground. The rolling map display shown in Figure 8 illustrates only 8 channels with a plan view on the left hand side and a cross section on the right hand side as well as navigation data. More sophisticated signal processing techniques can be applied to multi-channel data [4].

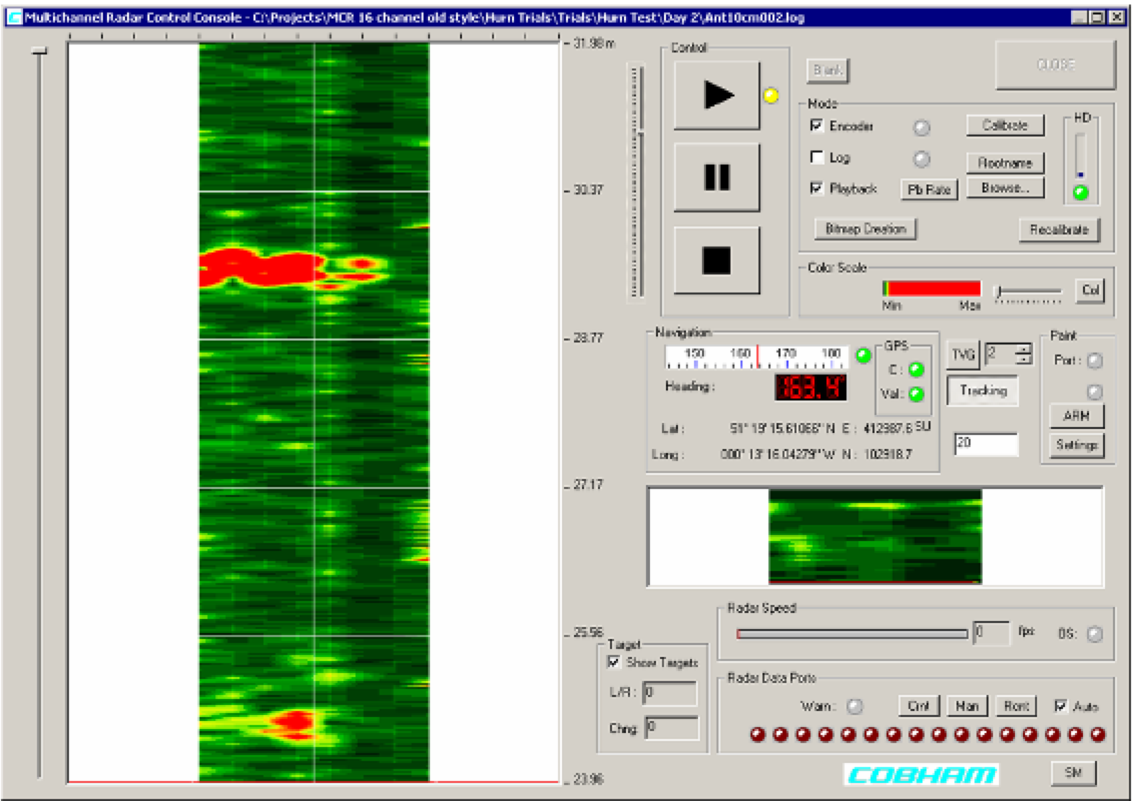

Figure 8 Rolling map display of vehicle radar

Challenges

The main challenge for GPR for landmine detection is to achieve a very high probability of detection with a commensurately low false alarm rate and this can be achieved by means of target identification.

Hand-held landmine systems are more limited in the signal processing algorithms that can be applied because they usually only have a single transmit-receive antenna pair compared with vehicle based systems that use arrays of antennas and, with only a few exceptions, do not form an image. Research into target discrimination based on the analysis of A-scans by means of complex resonances, wavelets, time- frequency characteristics, Neural networks, fuzzy sets, Gaussian mixture models, order statistics, template matching, has been carried out. Processing methods based on time-frequency characteristics are reported in the literature and the Short Time Fourier Transform (STFT) can also be used to provide discrimination between of clutter targets and AP mines [5], [6].

The signal and image processing options for vehicle based landmine detection are more extensive because the radar and its platform generate 3-D data. In general, vehicle based systems concentrate on anti-tank landmines because it is difficult to achieve adequate cross range resolution at realistic budgets. Options for signal and image processing include image inversion and synthetic aperture techniques for image enhancement principal component analysis (PCA) and independent component analysis (ICA) techniques and hidden Markov models.

Summary

Research on GPR technology and signal processing has proved a popular topic in many countries and institutions. However, the wide range of soil types, surfaces topographies, buried clutter and the wide range of targets lead to an ill-posed environment in which the end user demands a very high performance and leads to a problem space which will require much further work to meet the customer needs. Radar detection of buried landmines is thus practically and intellectually challenging but, much of the output, particularly in terms of classification, has yet to be implemented into real time systems. This would appear to be the challenge for the next generation of equipment.

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