ULTRA-WIDEBAND 3-DIMENSIONAL IMAGING (UWB 3D IMAGING)

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ABSTRACT

Ultra-wideband (UWB) radar has many potential applications that require systems offering low-cost, compact, real-time imaging with good resolution and the ability to penetrate materials. Typical applications include:

- medical imaging,
- people imaging,
- baggage scanning,
- through-wall imaging, and
- stand-off detection of threat objects concealed under clothing.

Systems need to operate with both stationary and moving targets and in highly cluttered environments, including indoors and near buildings. Therefore, techniques for resolving 3D clutter are required.

A potentially low-cost and lightweight UWB 3D imaging radar system demonstrator has been developed and implemented at Roke. The demonstrator operates within the FCC power spectral limits, whilst providing enough power for a wide variety of radar imaging functions.

The system uses frequency-modulated continuous-wave (FMCW) radar and linear one dimensional planar antenna arrays (horizontal and vertical polarisations) arranged in a bistatic configuration to synthesise a 2D planar aperture. 3D images are then formed by combining the backscatter data over the measured frequency band for each spatial coordinate of the 3D scene being imaged.

This paper presents the UWB 3D imaging system, the imaging algorithm and the experimental results for the medical imaging and people/baggage scanning scenarios considered. The results indicate that the system has excellent sensitivity, providing:

- clear detection of small targets with relatively high ε_r within homogeneous medium, and
- accurate location of targets within 2D /3D scenes.

Further advanced developments of the demonstrator are proceeding at Roke for a range of applications.

Keywords: Ultra-wideband, radar imaging, bistatic radar, two-dimensional, three-dimensional, medical imaging, people imaging, baggage imaging, security imaging, through-wall imaging, IED, mine, stand-off, algorithm.

INTRODUCTION

Ultra-wideband (UWB) signals originated from research and development work on high resolution radio-frequency (RF) radar systems in the 1950-60s. The current FCC regulations in the US, define a UWB signal as having an absolute bandwidth which exceeds 500 MHz or fractional bandwidth over 20%. The FCC frequency band assigned to UWB systems extends from 3.1 GHz to 10.6 GHz, i.e. a bandwidth of 7.5 GHz centred at 6.85 GHz.

Recently there has been noteworthy interest in the development of novel low cost lightweight people imaging, baggage scanning and medical imaging techniques using UWB signals as the basis.

In researching, developing and building and testing a relatively high-resolution UWB 3D imaging system demonstrator, our main objective was to determine whether 3D UWB radar images provide useful information for a variety of applications and to explore the radar requirements and estimated performance for such applications.

APPLICATIONS

For the people imaging and baggage scanning applications, there is considerable interest in cost effective imaging techniques which can be used to detect threat objects (e.g., weapons and explosives) concealed under clothing or in bags.

For a long time, RF and microwave engineers have dreamed of using non-ionising electromagnetic waves to image inside the human body in order to detect anomalies. Over the past several years, significant progress has been made towards making this dream a reality. In the medical application, the relative dielectric properties of living tissues are very varied offering large contrasts to the UWB imaging modality. In particular breast cancers have been shown to have dielectric constants and RF conductance that are more than a factor of 5 greater than normal healthy breast tissues.

In summary, the applications where we see significant potential for UWB 3D imaging include [1]:

- Diagnostic medical imaging and healthcare where there is the possibility of providing equipment much closer to the local point of care
- People imaging and baggage scanning for the detection of concealed weapons and explosives
- Through-wall 3D imaging for covert surveillance and reconnaissance

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- Vehicle-mounted for short-range situational awareness in complex environments (e.g. for unmanned ground or air vehicles)
- Improvised Explosive Device (IED) and mine detection.

Many other applications are envisaged for UWB 3D imaging where there is a need for a system offering low cost, lightweight / compact, real-time 3D imaging with adequate resolution and the ability to penetrate complex materials.

REGULATIONS

In the past, UWB technology development has been closely aligned to the evolution of US regulations. In 1989, the FCC revised its regulations for unlicensed transmitters and specified a general limit for transmissions in Part 15 rules [2].

The FCC rules are designed to protect specific sections of the spectrum allocated to systems which are particularly sensitive to noise-like interference (e.g., GPS frequency band). The permitted level is the FCC spectral limit of -41.3 dBm / MHz Effective Isotropic Radiate Power (EIRP) in the UWB band 3.1-10.6 GHz. There are a number of frequency masks for different use and, the indoor and outdoor masks are illustrated in Figure 1 [3]. The FCC and draft ETSI indoor masks are illustrated in more detail in Figure 2 [4].

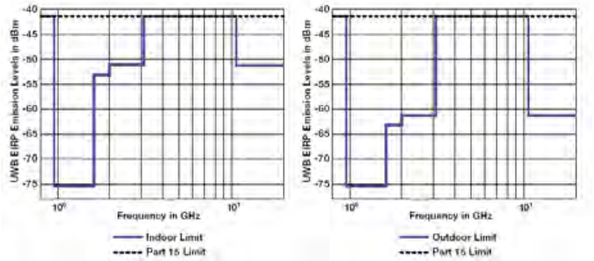


Figure 1: FCC Part 15 Spectral Mask

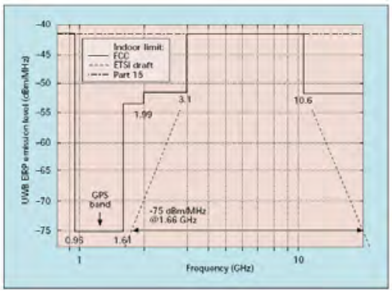


Figure 2: FCC Part 15 and ETSI Spectral Masks for Indoors

DEMONSTRATOR

The demonstrator equipment set up is shown in Figure 3. The equipment can be mounted in a standard 19 inch rack frame. The equipment consists of four transceiver / antenna units, configured for operation as two independent bistatic radars (i.e. two transmitter / receiver pairs, operated non-simultaneously). One of the radars is configured for operation at co-polar vertical (VV) polarisation and, the other radar unit for operation at co-polar horizontal (HH) polarisation.

For each radar, the UWB RF switching controller software was programmed to switch the transmit (Tx) slowly through elements 1-25 (25 consecutive cycles at each position), and the receive (Rx) quickly through elements 1-25 (1 cycle at each position). A frame of 625 cycles therefore contains data from each bistatic element pair.

Figure 3: UWB 3D Imager demonstrator experimental set-up

Bistatic radar data has been captured using each transmit/receiver (Tx/Rx) pair in turn and processed using the 3D imaging algorithm. The results were analysed to determine the applicability of the UWB 3D imager to the medical imaging and baggage / people scanning scenarios being considered.

ALGORITHM DEVELOPMENT

This section describes the 3D imaging algorithm used to process UWB data, and the techniques used to display the resultant 2D and 3D images.

3D Imaging Algorithm

A number of different algorithmic approaches have been considered in order to extract 3D information from the UWB data. The two most appropriate algorithms for both the medical and people scanning applications were using 3D (frequency domain) matched filtering and, 2D (range domain) matched filtering repeated for a number of positions to build a 3D image. These two algorithms were implemented for comparison. The 2D matched filtering approach was selected as it was significantly faster (typically 25 times faster) with no significant reduction in image quality.

3D Image Display

The simplest way to display UWB 3D image data is as a 2D slice in a given plane, or a series of slices in parallel planes “stepping through” a target. The images shown in this paper are typically vertical slices, i.e. a plane parallel to the UWB arrays, at a given range from the radar. This is an intuitive view of the scene, although an image could be produced in any arbitrary plane by specifying a different set of voxel coordinates.

A 3D data volume may be rendered for display on a 2D screen or page, using colour, lighting and transparency to aid human interpretation of the image. The 3D images shown in this report are “isosurfaces” or 3D contour plots, in which the plotted surface connects all points at a certain intensity threshold value (and therefore encloses all points exceeding this threshold).

Interpretation of UWB 3D images may be enhanced by comparison and overlaying with corresponding visual images. This requires accurate registration of images.

MEDICAL IMAGING

This section describes the experimental trials to determine the applicability and performance of the UWB 3D radar imaging demonstrator for medical imaging applications. In particular the study focused on UWB 3D imaging radar technology as a diagnostic indicator in support of the detection of anomalies (e.g., cancers) for medical and healthcare applications.

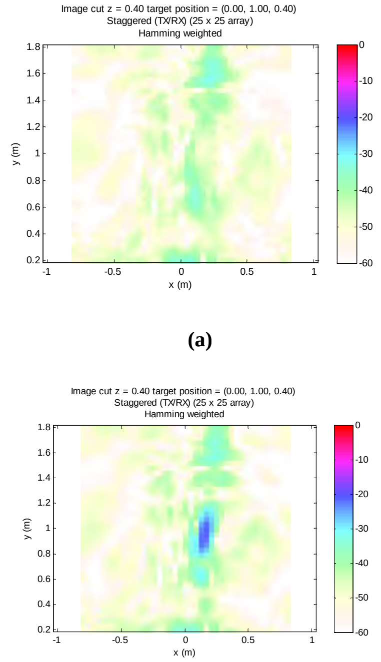
Scaled Targets

The current antenna array is designed for use in air (ε_r = 1) and is therefore much larger than an antenna array intended to launch microwaves into human tissue, which has a much higher ε_r of 15.7 [5]. It was therefore decided to produce a model, scaled in terms of size and ε_r to evaluate the possible detection of anomalies (e.g., tumours). The size has been increased by a factor of 4 ($\approx \sqrt{15.7}$) and the dielectric constants of the materials have been reduced by a factor of 15.7 so that healthy tissue can be represented by air and anomalies (e.g., tumours) can be represented by a medium with a dielectric constant of approximately 3. Therefore, for example, to a reasonable approximation, a 1cm tumour 10cm deep in healthy tissue can be represented by 4cm plastic sphere 40cm from the array. Target spheres of various sizes and materials were therefore imaged at a range of 40cm from the array.

Experimental Results

This section presents the results of the experimental measurements to determine the applicability of UWB 3D imaging radar to the medical imaging scenario being considered.

A small plastic sphere (diameter = 4cm) filled with silicone compound was used to represent a 1cm diameter tumour. The sphere was placed on an expanded polystyrene cone (dielectric constant ≈ 1) at a range of 40cm in front of the UWB arrays, equivalent to a depth of 10cm in healthy tissue. 2D images (vertical slices at the target range of 40cm) formed from UWB data, with and without the target present, are shown in Figure 4. The ‘tumour’ is clearly visible when present. The dynamic range of the image may be further improved by subtracting the reference (no target) data set. A 3D isosurface image of the 'tumour', after background subtraction applied, is shown in Figure 5.



(a)

(b)

Figure 4: Scaled target representing 1cm tumour 10cm inside body – (a) without target; (b) with target

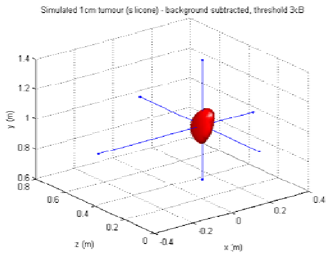


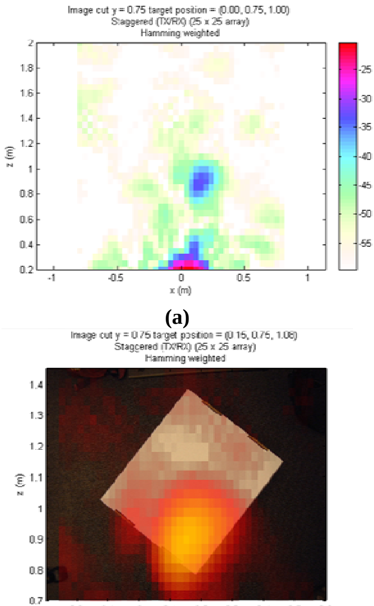
Figure 5: Scaled target representing 1cm tumour (background subtraction applied)

Following the successful detection of the 40mm sphere (which represents a 1cm tumour) some smaller targets were imaged. These include an irregular silicone rubber structure representing an irregular 1cm x 0.25cm anomaly. A range of different size plasticine spheres were also tested, the smallest of which representing a 0.25cm anomaly. These targets were again clearly visible and accurately located within the 2D and 3D UWB images.

To simulate an extra discontinuity within the body the simulated 1cm diameter tumour target was placed in a container of material with a dielectric constant of 1.6, which is half the scaled dielectric constant of the tumour shown in Figure 6. The simulated tumour is visible at approximately 1m range (equivalent to approximately 25cm in healthy tissue). The background subtraction technique was not applied in this case and the red area at close to zero range in Figure 6 is the direct breakthrough from the transmitter to the receiver.

Figure 6 (b) shows the UWB image overlaid on a photo of the rectangular container, accurately indicating the true position of the simulated tumour close to the front corner of the container. This image illustrates how UWB of the images may be presented in a final system to assist user/operator interpretation.

A 3D UWB isosurface image of the simulated tumour is shown in Figure 7. This demonstrates that the wanted target can still be isolated and located within the volume plotted, despite the presence of the intermediate dielectric medium.



(a)

(b)

Figure 6: (a) Plan view of dielectric medium (dielectric constant 1.6) with buried 40mm silicone compound target; (b) Overlaid UWB image and photo for buried 40mm silicone target

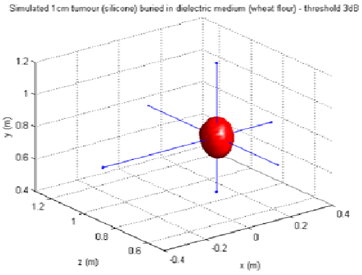


Figure 7: Dielectric medium (dielectric constant 1.6) with buried 40mm silicone compound target

Application Analysis

The experimental results presented for the medical imaging scenario demonstrate:

- Excellent sensitivity - clear detection of small targets with relatively high εr within homogeneous medium;
- Accurate location of targets within 2D / 3D imaging scenes of volumes.

The results also indicate:

- The current demonstrator does not have enough resolution in UWB images to show the shape of targets;
- Resolution could be improved using increased bandwidth and/or larger array apertures and/or different antenna geometry;

In summary, scaled experiments suggest that UWB imaging has clear potential for the detection of anomalies (e.g., tumours) in healthy tissue, i.e. assuming the scaled measurements are an accurate representation of what can be achieved with an antenna matched to an impedance of healthy tissue then a UWB medical imaging system which is placed in contact with the area of the body being imaged may be practical.

PEOPLE & BAGGAGE IMAGING

This section describes the experimental trials and results to determine the applicability and performance of the UWB 3D radar imaging demonstrator for baggage/people imaging applications. In particular the study has focused on UWB 3D imaging radar technology as a baggage & people imager for security, crime detection and prevention applications (e.g., detection of concealed threat objects such as weapons at transportation terminals and similar).

Experimental Results

The experiments were carried out using the following targets:

- Person without concealed objects.
- Luggage containing innocent, ordinary items, for example a coat in a rucksack, laptop computer in laptop bag, etc.
- Simulated nail bomb concealed in luggage – a plastic bottle with nails attached to the outside, placed in a rucksack.
- Simulated Bomb with ball bearings and Plasticine (to simulate plastic explosive) – placed inside a briefcase or laptop bag.

Person only

Data was captured for a person at approximately 1m range in front of the arrays, standing facing the arrays with hands clasped behind their back (Figure 8). The resulting 3D images in Figure 9 clearly show the shape of the subject (head, torso, upper arms and upper legs). As expected, there is some distortion due to the particular radar geometry used, compared to the true physical shape, but the dimensions of the imaged subject are approximately correct.

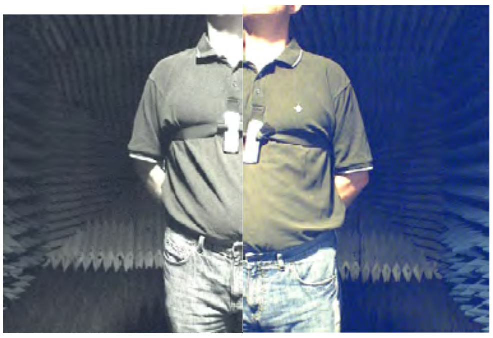
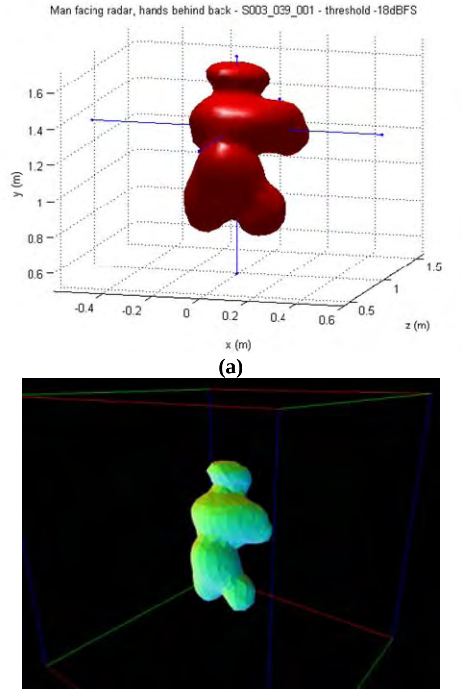


Figure 8: Images of person from left and right cameras



(a)

(b)

Figure 9: (a) 3D image of person front on to radar and, (b) rotated to show side on view

Targets in Baggage

A rucksack was placed on a 0.6m high expanded polystyrene block, in front of the arrays at approximately 1m range. UWB data was captured with the rucksack containing: (i) a cotton lab coat, and (ii) the simulated nail bomb. The results indicated:

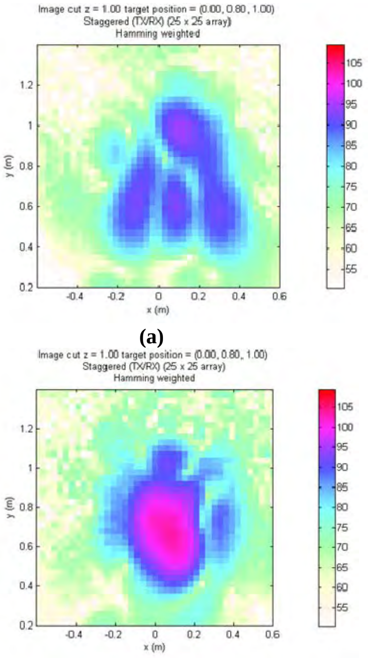
- An observable difference in the shape and position of the object in the UWB image, but the magnitude is similar to the lab coat,
- Reflection from the nail bomb is significantly stronger than that from the lab coat,
- Resolution of the UWB demonstrator is not sufficient to produce reliable information on the shape of the object within the bag for identification purposes.

A second series of experiments were conducted using a briefcase (i) completely empty; (ii) containing a hardback A4 logbook; and (iii) containing a simulated bomb. The briefcase and simulated bomb are shown in Figure 10.

2D and 3D images formed from the UWB data are shown in Figure 11. Images of the empty briefcase (Figure 11a) show reflections predominantly from the front surface and bottom corners. Images of the briefcase containing the logbook are similar, with slightly more power reflected. Images of the briefcase containing the simulated bomb (Figure 11b) show significantly more power reflected, with the return from the bomb masking the return from the briefcase such that most of the "shape" of the preceding 3D UWB images is lost. The resolution of the current UWB demonstrator is not sufficient to produce reliable information on the shape of the object within the bag for identification purposes.

(a) **(b)**

Figure 10: (a) Briefcase on polystyrene block (b) containing simulated bomb plastic and ball bearings



(a)

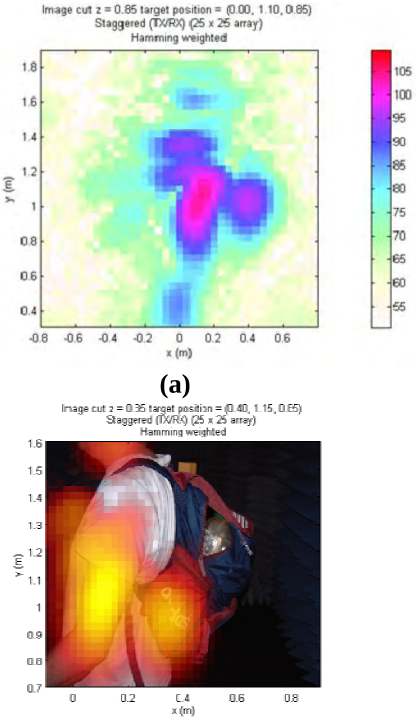
(b)

Figure 11: (a) UWB image of front view of empty briefcase, (b) UWB image of front view of briefcase containing simulated bomb ball bearings and plastics

Targets on People

UWB data was collected for a human subject wearing a rucksack (Figure 12), with their left side on to the UWB arrays with the rucksack containing (i) a cotton lab coat and (ii) the simulated nail bomb. The outline of the subject's head, trunk, left arm, left leg and the rucksack were visible to some extent in the UWB images formed (Figure 13). The right hand side of the subject's body was mostly shadowed. The reflection from the rucksack is somewhat larger when containing the nail bomb compared with the lab coat, but there is not enough resolution to reliably discriminate a threat object.

Figure 12: Subject wearing rucksack (containing simulated nail bomb)



(a)

(b)

Figure 13: (a) Subject wearing rucksack containing coat left side on; (b) Subject wearing rucksack containing nail bomb – photo and overlaid UWB image

Figure 13 also shows how, in principle, visual and UWB images could be combined to aid analysis. In this example, a 2D UWB image (vertical slice) is scaled and overlaid on the photograph of the subject and rucksack containing the nail bomb. Clearly, the UWB image does not register/align with the photo accurately. It is expected the registration process accuracy may be improved through further analysis of the UWB images content and improving the demonstrator's imaging resolution performance.

Application Analysis

The experimental results demonstrate:

- Good imaging of large target (outline of human subject)
- Resolution of current UWB 3D demonstrator not sufficient to discriminate threat objects as part of complex targets

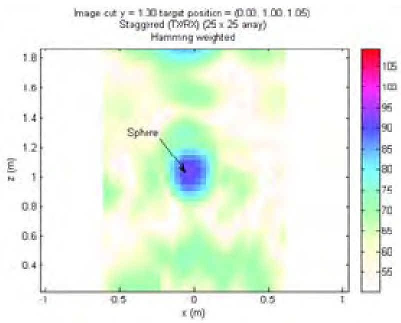
To enable reliable discrimination between threat and non-threat objects, it would therefore be desirable to improve the resolution of the system in both cross range and down range. This could be done by increasing the array size relative to the wavelength (for improved cross range resolution) and experimenting with different antenna geometries/configurations and increasing the UWB sensor bandwidth (improved downrange resolution).

THROUGH-WALL 3D IMAGING

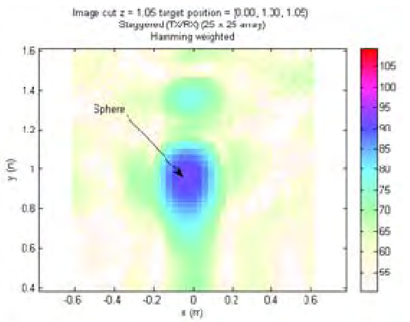
A further experiment was conducted using the UWB 3D hardware to demonstrate the basic feasibility of through-wall 3D imaging. The equipment was set up with the array faces nearly in contact with a 10cm thick plasterboard partition wall (approximately 1cm separation between arrays and wall), as shown in Figure 14. Data was captured with targets deployed in the 2m wide corridor on the other side of the wall. Figure 15 shows the corresponding images with background subtraction applied. The metal sphere is revealed as the single dominant feature within the image.

(a) **(b)**

Figure 14: (a) UWB 3D demonstrator setup for through wall measurements; (b) Scene for through wall measurements with metal sphere target present, UWB 3D demonstrator behind wall on left of photograph



(a)



(b)

Figure 15: Through wall image of corridor and metal sphere after background subtraction – (a) plan view, (b) vertical slice

CONCLUSIONS

Medical imaging

The results of the medical UWB images of scaled targets look promising, and demonstrate excellent sensitivity and accurate location of small objects. If this is representative of tumours in healthy tissue then UWB imaging may have the potential to replace X-Ray machines and be used in some cost sensitive applications, e.g. as a diagnostic indicator in support of the detection of anomalies (e.g., cancers, tumours) at Doctors' Surgeries and Community Healthcare Centres & Clinics.

Further experimental work should be carried out using a suitable scaled antenna and matching medium, to confirm the detectability of realistic anomalies in a representative medium and people.

A final medical imaging system may require high resolution in any dimension. This could be achieved by increasing the UWB sensor operating bandwidth and doubling the size of the antennas, resulting in a much smaller and more compact antennas of approximately 15-30cm long (depending on the imaging scenario) after scaling for the permittivity of healthy tissue, and/or using a different antenna geometry or configuration for the application.

Baggage, People imaging

The results of the people and baggage scanning experiments show that the resolution of the current UWB 3D demonstrator is insufficient to reliably discriminate between “innocent” subjects and those carrying potential threat objects. However, the UWB signals do appear to penetrate clothes and baggage materials.

For reliable imaging performance, resolution improvements may be desirable in each dimension. The down range resolution of the current demonstrator could be improved if the UWB sensor and antenna operating frequency bandwidth could be increased. Cross range resolution could be improved from at stand-off range by increasing the array aperture size.

Further work is required to assess possible alternative radar geometries which combine very high down range resolution with multiple views of the target.

Through-wall imaging

The UWB 3D imaging equipment has been used to demonstrate the basic feasibility of through-wall 3D imaging. Metal spheres and people have been observed through stud walls in a typical office environment.

Algorithms

The 3D imaging algorithm developed has been shown to be capable of generating high quality images from UWB 3D data. The algorithm is significantly faster than a full 3D matched filter, with no significant reduction in image quality.

A 3D data volume may be rendered for display on a 2D screen or page, using colour, lighting and transparency to aid human interpretation of the image.

In summary, UWB 3D imaging radar technology has many potential applications including: (1) a diagnostic indicator in support of the detection of anomalies (e.g., tumours, cancers) for medical and healthcare applications, (2) a baggage & people imager for security, crime detection and prevention applications (e.g., detection of concealed threat objects such as weapons at transportation terminals, etc.).

Further advanced developments of the demonstrator are taking place at Roke for a range of applications.

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