Ultra Wide Band (UWB) Impulse Radar Imaging

For

Inter-Vehicle Embedded Simulation (INVEST)

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ABSTRACT: *Field training using embedded simulation on board mobile combat vehicles is a first-of-its-kind challenge being undertaken by STRICOM's Inter-vehicle Embedded Simulation (INVEST) Science and Technology Objective (STO) research program. To effectively use virtual imagery on real terrain, real objects must be imaged and located on the terrain so that realistic occulting can be applied to overlayed virtual images. This paper describes an approach to achieving the needed real-time imaging and registration capability using an innovative Ultra Wide Band(UWB) radar as an imaging sensor.*

Since a UWB mobile communication LAN is emerging as an effective INVEST simulation network solution, the potential for realizing the imaging sensor functionality as a dual-use extension of the same equipment is also attractive. INVEST application issues are examined and expected range and resolution are quantified using earlier analytical studies, present-day precision pulse generation equipment capabilities, and projected UWB radar equipment availability. Potential tactical operations applications of the UWB embedded simulation training research and development are also suggested.

1. Introduction

The STRICOM sponsored Inter-Vehicle Embedded Simulation Technology Science and Technology Objective (INVEST STO) research program has a requirement for a sensor system capable of digitally imaging and precisely locating real objects on the training, or actual battlefield, in near real-time. Subsequent processing must then convert the digitized images into virtual objects on a corresponding simulated battlefield so as to accurately occult virtual opposing force objects being overlaid on vehicle vision blocks. A scanning array radar based on UWB impulse radar technology is being evaluated that shows promise as a potential solution.

A UWB mobile communication LAN is emerging as a preferred simulation network technology solution (see companion paper 98F-SIW-035). The potential for realizing the needed imaging sensor functionality from an extension of the same equipment is an added benefit. Availability of UWB communication/impulse radar components in CY98, and increasing commercial product activity in CY99, support the INVEST development schedule as well as prototype demonstrations.

Broad application of the UWB technology to general commercial and military imaging problems is expected to accelerate in the next 2 to 3 years. The multi-application commercial potential of the technology should indirectly benefit INVEST cost, schedule and performance potential and reduce availability risk.

A specific instance of commercial demand for the UWB radar technology is remote imaging of concealed objects and personnel inside of walled enclosures, or even underground. The broadband electromagnetic emissions at Gigahertz (GHz) frequencies readily penetrate non-conducting structures, and the impulse approach is not sensitive to multipath fading, or urban narrow-band interference.

Commercial and military applications to law enforcement, urban military operations, automotive safety devices, covert surveillance, and secure communications applications are also being pursued, Reference [1].The US Army is also developing side and forward-looking, on-the-move mine detection equipment using the UWB radar's in ground imaging features. This work, and a large body of experimental data, were presented at a recent UWB Radio Workshop, Reference [1].

These programs have similar requirements to the INVEST program; their development investment can be leveraged toward meeting INVEST objectives. Use of the impulse radar approach for low-altitude air defense is also being researched. Stealth measures that are used to fool narrow-band radars are far less effective with UWB systems. Growing development interest reinforces INVEST application decisions and potentially reduces longer-term investment required to achieve a fielded system.

2. Statement of the Problem

Field training using embedded simulation on board mobile combat vehicles is a first-of-its-kind challenge being undertaken by STRICOM's INVEST STO research program.. To effectively use virtual imagery on real terrain, real objects must be imaged and located on the terrain so that realistic occulting can be applied to overlaid virtual opposing force objects.

Geo-location of imaged objects in a field of view ranging from a few meters to a few kilometers, with resolution of a centimeter, is a particular challenge. Visible light systems using video camera sensors have shown proof of principle for image capture, object detection, and overlaying. However, terrain registration for occulting virtual imagery is not possible without accurate relative object location.

Laser ranging has been shown effective in positioning and occulting. However, it is costly and requires pointing stability that may be difficult to achieve in mobile operations. Note that objects at long ranges require less positional precision and more of a detection function than an imaging function to adequately represent human perception of battlefield information.

Equipment must be small, or configurable to fit into the limited available space in already cramped war-fighting vehicles. In addition, this equipment must be rugged, reliable under battlefield conditions (including urban terrain), and simple to use. These features encourage minimal equipment solutions and thus make dual use of common equipment appealing.

Low power, covertness, jamming resistance, and the ability to operate concurrently with existing military and commercial communication systems will also be important for battlefield mission rehearsal. UWB radar has characteristics that effectively respond to these requirements and consequently is being investigated as a candidate technology.

The imaging equipment must also use standard interfaces and protocols to readily integrate with existing vehicle power and communication subsystems. Subsequent processing to properly relate the imaged elements with virtual elements on the simulated battlefield must then be provided making use of the precision geo-location capability of the radar sensor or an adjunct ranging system.

The potential for realizing a dual-use imaging sensor with inherent precision geo-location capability from an extension of the UWB communication LAN capability is beneficial for minimizing components and vehicle integration effort. The UWB LAN capability is separately described in a companion paper (98F-SIW-035).

The availability of UWB radar sensor components during the INVEST development window is an obvious requirement and problematic for emerging technology solutions. At the present time, prototype UWB impulse radar ASIC components have been produced with additional units expected in late CY98. Planned commercial imaging product activity in CY99 and CY00, if it stays on track, will support the INVEST development schedule and the INVEST prototype imaging demonstrations in FY01.

3. The INVEST Sim Network Environment

A warfighter-centric focus guides the INVEST development requirement definition. Consequently, to define surrogate sensor and LAN equipment parameters, a variety of Army ground vehicle engagement scenarios were used to scope equipment operating parameters.

For example, range requirements for engagements were estimated from field manual movement-to-contact formations. Results of this assessment indicates that the battle area falls within a 1 to 2 Kilometer radius for a tank company, with tank platoon elements seldom separated by more than 300 meters.

This is illustrated by the tank company moving to contact in a wedge formation with terrain scales shown in Figure 1. Note the single dashed red lines depicting communication links and multiple red lines indicating imaging radar scans. Vehicle separation is obviously terrain dependent, but this approach provides a reasonable estimate of the nominal inter-vehicle communication range requirement.

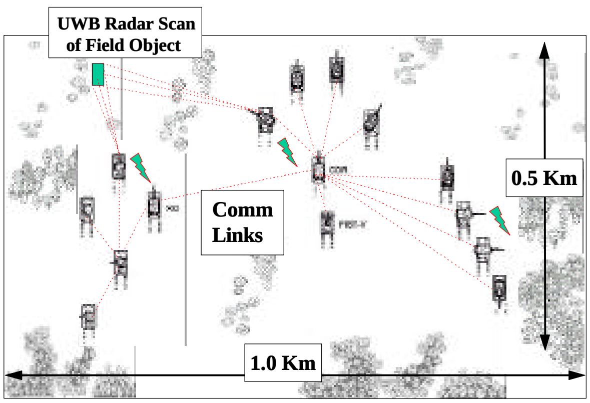

FIGURE 1: UWB Image scans and Com Links – Armored Company -Movement to Contact

For terrain object imaging, however, some added range between engaging opposing forces must also be included. This consideration is estimated to double the required viewing range. Imaging at these ranges has never been attempted and may be a governing constraint. This is mitigated by the reduced precision requirement at long range noted earlier.

Real world tactics tend to close the separation distance in cluttered terrain and expand it in open plains or desert terrain. This also fits well with the operational reach of the UWB radar that can extend to multiple kilometers in open terrain and at higher power levels and even further with elevated or airborne antenna.

For initial static and mobile proof of concept experiments and later prototype training demonstrations, the INVEST imaging sensor network will be limited to four vehicle armored platoon size units. Imaging array equipment and network capabilities are sized to this small unit problem set as being most typical of the near term training objective. To better understand the projected advantages of the UWB radar technology, a summary technical overview of key UWB radar features is provided in Section 4.

4. UWB Radar Imaging Overview

4.1 Radar Imaging of 3D Objects

A single impulse radar transceiver would suffice to achieve a precision detection and location (range, angle- i.e. 2D) capability. To achieve image generation, a multiple transceiver array is necessary to generate a correlated 3-dimensional view of the target. For the INVEST concept study, a transceiver antenna array would be mounted on the external surface of the vehicle.

Figure 2 shows a notional view of a UWB radar array consisting of a ring of conformal antenna circling the turret of a main battle tank. This corresponds qualitatively to configurations analyzed in References [1] and [2]. Multiple 2D views are captured by the antenna array that are then computationally merged using processing techniques similar to those developed for medical Computer-Aided Tomography (CAT).

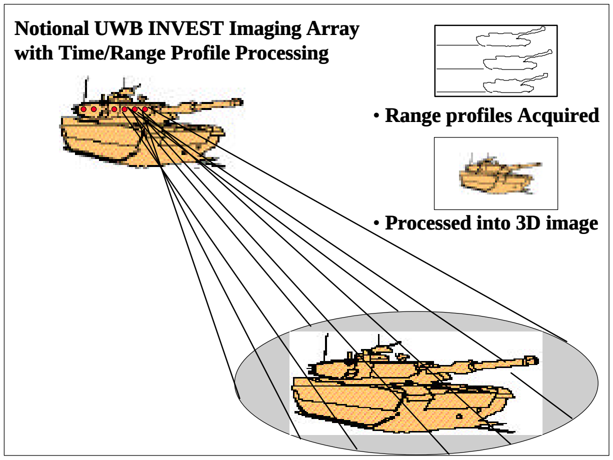

FIGURE 2: UWB Radar 3D Image Acquisition and Construction

Pertinent features of the analyses described in References [2] and [3] are used here to anticipate the INVEST application result. Similar techniques for use in a proposed advanced ground-penetrating mine detection radar using the UWB impulse approach are described in Reference [4].

4.2 How UWB Radar Imaging Works

An Impulse radar transceiver emits a train of very narrow pulses. The transiently radiated field impinges on objects in its field of view and returns a reflected portion of that energy to a correlating receiver. Pseudo-random coding of the pulse train creates a very covert signal and allows the correlating receiver to extract very low energy reflected signals from background noise.

Reference [5] provides an analysis of the reflected field of an incident impulse. It concluded that the early time response of the reflected impulse behaves similarly to optical point scattering, and is independent of the object shape. This relates to the known ability of UWB impulses to detect stealth designs that are principally based on shaping the target object. This same result also implies that well established optical/sonar image processing techniques can be used for imaging.

Reference [3] examines the use of a circular array of 10 UWB impulse transceiver elements on a 0.1-meter radius circle using an EM field analysis simulation. The analysis concluded that precision angular resolution was achieved with sparse arrays on the order of the wavelength of the single pulse cycle divided by the circular diameter (e.g. $(1x10^{-10}sec)$ x $(3x10^{7}m/sec\}/(10^{-1}m = 3x10^{-4}radians))$.

UWB systems were shown to achieve higher resolution at much lower, more practical parameters, and with fewer array elements than conventional resonance radars. The UWB radar array also demonstrated the ability to focus received energy into the main lobe by adding elements. This practically eliminated the side-lobe effects that limit the sensitivity of conventional systems.

Reference [4] provides a similar analysis for a single-transceiver radar, but introduced a model of the matched filter processing element of the correlating receiver. This analysis made quantitative, practically achievable estimates of range and velocity accuracy as well as resolution.

Based on the typical pulse parameters identified, the results obtained are shown in Table 1. The study also concluded that impulse radar is capable of achieving a range resolution that is almost impossible for conventional radar.

Pulse rise time = 100 ps; Pulse Energy ratio = 10
Number of pulses = 100; Repetition period = 1 ms

Range Accuracy	0.0021 m
Range resolution	0.187 m
Velocity Accuracy	0.0081 m/sec
Velocity Resolution	0.187 m/sec

TABLE 1. Estimated UWB Radar Performance

A major advantage of UWB impulse radar is the ability to obtain excellent resolution properties at much lower absolute frequencies than conventional radar. This plays a significant role in situations where penetration through foliage, and all-weather use is important. Correlated multiple-element arrays should allow improvement beyond the Table 2 estimates.

A digitally controlled, beam-steered UWB array resembling basic features of that needed for INVEST was constructed, tested, and is described in Reference [6]. Although developed for ground penetration survey from an aircraft, the observed results confirmed the theoretical analyses cited above, and lend additional confidence to the proposed INVEST application assessment and prototype assembly and demonstration.

Imaging the obtained returns from the steered UWB array is principally a matter of implementing the appropriate processing software for a correlated merge of multiple 2-dimensional images of the target object(s). Although non-trivial, the required processing software and hardware is equivalent to mature algorithms and computational processing components used in related ultrasonic imaging, CAT scan x-ray, or Magnetic Resonance Imaging (MRI) processing

Mobility issues have not been sufficiently addressed at this point to render quantitative performance estimates. An evident issue will be the speed of capturing a set of images that could introduce image correlation ambiguities, or blurring. It is estimated that near term available fast, digital-memory systems can capture images at adequate speeds; processing could be done on a queue of captured images to meet a 30-frame/sec rate simulation requirement.

Processing to meet this real-time simulation requirement will be challenging, and likely require parallel processing of the multiple 2D image merge. For longer range objects, 3D imaging may not be important to the occulting function. This could reduce processing requirements significantly and will be an important criteria to define during prototype testing.

Image enhancement and platform motion compensation techniques have been effective for sharpening images for optical imaging systems. Similar approaches would be reasonable to employ and effective if this becomes a significant consideration. Additional aspects of the UWB imaging process can best be understood by comparison between conventional Ground Penetrating Radar(GPR) and UWB radar characteristics. This comparison is presented in Section 5.

5. UWB vs. Conventional Radar Imaging

The following UWB radar imaging assessment is based on excepts from Reference [3]. While written in the context of imaging with an UWB array used as a ground penetrating radar, the technical discussion and essential features apply to the above ground INVEST imaging application. The UWB imaging concept described here is characterized by four key elements:

- Transmission and reception of Gaussian monocycles
- An ideal antenna design
- Use of a correlating receiver acting as an ideal matched filter
- Use of tomographic processing for 3D image construction.

5.1 Gaussian Monocycles

Shown in Figure 3 is a Gaussian monocycle and its corresponding frequency power spectra. Because of the pulse shape, the monocycle is characterized by very wide bandwidth with a (roughly) even distribution of energy. This results in two key advantages. First, because of its high bandwidth, the monocycle is capable of resolving even very small objects. Second, all of this is accomplished at the lowest possible electromagnetic frequency, thus giving maximum resolution with the least loss due to absorption by the Earth for ground penetrating applications. In the case of INVEST, foliage, weather and buildings in urban environments or similar battlefield clutter are included.

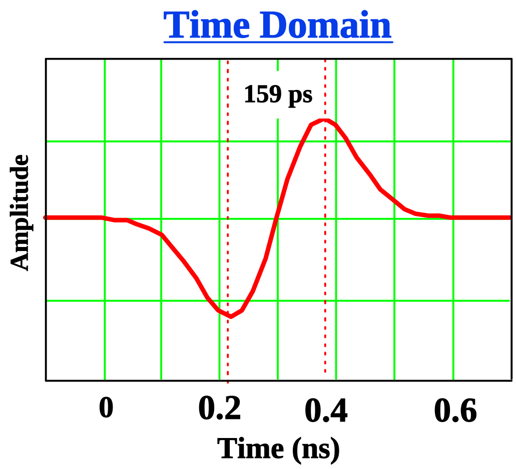

FIGURE 3: Gaussian Monocycle & Corresponding Frequency Spectra.

Not only is the shape of the monocycle important, but the method by which the monocycle is transmitted is equally important. Instead of transmitting monocycles at a constant repetition rate, the exact moment that a pulse is transmitted is dithered slightly in time. In other words, while the *average* time between pulse transmissions (or pulse repetition rate) is constant, the time between transmitted monocycles is irregular. This is illustrated in Figure 4.

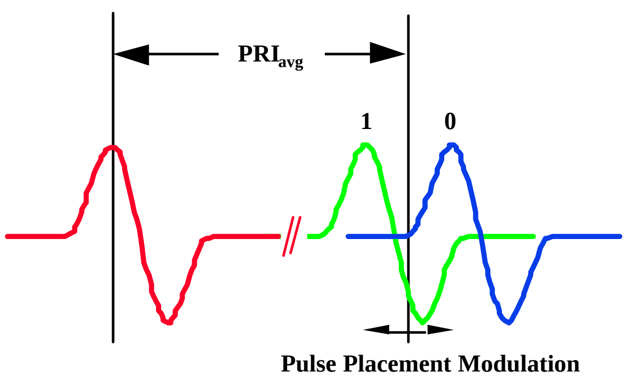

FIGURE 4: Monocycle Placement Variation.

In fact, this variation, is purposely made pseudo-random. Pseudo-random dithering of the pulse transmissions results in a number of unique advantages: First, dithering guarantees that the bandwidth of the signal is a function of the characteristics of the *monocycle* and not the *repetition rate*. Consequently, the system bandwidth (and the corresponding system resolution) is constant and is independent of the repetition rate.

Second, since the signal is broadband, UWB radar transmissions are indistinguishable from noise. Therefore, UWB radar transmissions do not interfere with military or commercial radars and radios. Similarly, military or commercial radars and radios will not interfere with UWB radar systems either. In fact, as long as each UWB radar system employs a different pseudo-random dithering code, then multiple UWB radar arrays may be operated in close proximity. For example, time dithering reduces mutual interference with other units by at least 20 dB (100:1).

Third, because the pulses are not transmitted at a constant rate, mirages are greatly suppressed. Pseudo-random dithering actually reduces and eliminates mirages by a factor of 16 dB (40:1).

5.2 Antenna Characteristics

Through a combination of good engineering, successive iterations and some luck, Time Domain Corporation has developed a unique antenna shape that for land mine detection applications, has near ideal characteristics. The antenna:

- Is small
- Is simple
- Is inexpensive
- Has no ring down
- Does not distort transmitted or received signal
- Is phase linear
- Operates with 50-ohm cable
- Low-voltage operation & reasonably high power
- Planar (flat as opposed to a 3-D horn antenna)
- Is densely arrayable
- Antenna independent of the ground.

These performance characteristics make the antenna ideal for this application. Furthermore, it provides a data quality level unapproachable by conventional GPR technology. Ground penetrating radar systems utilize a sampler as a receiver. This produces a low instantaneous dynamic range and a high noise figure. In contrast, an UWB imaging radar makes use of a cross correlating receiver.

This approach is relatively common in communications applications and is one of the technical reasons why cellular phone operation has been successful. The UWB imaging radar receiver cross-correlates the received signal with the template Gaussian monocycle. In addition, the cross correlation is executed only at those times corresponding to pseudo-random dither variation. The characteristics of the transmission/reception system can be summarized as follows:

- The transmitted signal has an extremely wide bandwidth
- The transmit wave shape is known
- The transmit antenna does not distort the transmitted pulse
- The received signals are not distorted by the receive antenna
- The correlation is synchronized in time to the transmission
- The receiver has a process gain of 50 dB (100,000:1)

These characteristics make the receiver a coherent matched filter. This is the ideal receive circuit. Such a system produces the highest quality data for tomographic imaging. Furthermore, several UWB radar features converge to produce a critical additional UWB radar feature. Because:

- The UWB transmissions are wide band <u>and</u> independent of repetition rate;
- The antenna can operate at reasonably low voltage
- The signal is coherent.

Averaging can be used to improve the signal to noise ratio. For example, conventional GPR systems operate at a pulse repetition rate between 1,000 and 500,000 pulses per second. In contrast, UWB radar operates at 5 million pulses per second and are capable of significantly higher rates. UWB radar not only produces higher quality data per pulse but by averaging a higher total number of pulses, the overall signal to noise ratio is improved between 5 and 30 dB (orders of magnitude).

Finally, the numerical processing requirements are reduced. Correlation does not produce the mathematically intensive manipulations characteristic of regular GPR approaches. Instead, the required math is merely successive additions. This makes UWB radar data processing very fast. As a consequence, imaging can be performed on a near real-time basis, at a reasonable travel speed, with reasonable sized processors.

5.3 Tomography

Traditional GPR systems use non-tomographic techniques. To date, these approaches have proven unsuccessful for good resolution imaging. They have been unsuccessful for two reasons. First, traditional GPRs collect one dimensional data and then stack that information to form 2-dimensional images. Second, the 2D data is distorted by exisiting clutter that cannot be removed. As a result, interpretation of the 2-dimensional images becomes highly subjective.
By contrast, UWB radar collects two dimensional data and then uses tomographic processing to focus this data into three dimensional images. In this process, the images are spatially resolved and the clutter is removed. The analysis then becomes an exercise in classifying objects rather than one of deciding if the object is an image or a mirage.

The difference between traditional GPR and UWBT is analogous to the difference between chest x-rays and CAT scans. Like GPR, chest x-rays are 2-D images in that bones, organs and tissues are superimposed. the challenge to a doctor is to try to discern if a dark object is a tumor, or just overlapping images of different tissues. In contrast, a CAT (Computer Aided Tomography) scan allows all of these tissues to be spatially resolved in 3 dimensions. The spatial ambiguities are resolved and identification clear. Similarly, Ultra-Wide Band radar allows the user to visualize what is actually in the field of view.

5.4 UWB imaging radar vs. Conventional imaging radar

Table 3 compares UWB imaging radar with more traditional imaging radar approaches.

HIGH LEVEL ISSUES	CONVENTIONAL GP RADAR	UWB RADAR	UWB radar BENEFIT
Antenna Performance	• Antennas Ring • Requires Horns or Direct Contact with Ground	• Doesn't Ring • Antenna Isolated From Ground	• Higher Resolution Data • Independent from Ground • Portable
Antenna & Ground	• 2D Images Are Subjective	• 3D Tomography Separates	• Higher Quality Images

HIGH LEVEL ISSUES	CONVENTIONAL GP RADAR	UWB RADAR	UWB radar BENEFIT
Clutter	and Obscured by Clutter	Clutter From Images	For Subsequent Mine ID
EMI/EMC	• Noise Generator • Subject to Noise	• Dithering and Correlating Receiver Minimizes Noise Effects • Functions Below the Noise Floor	• Can Co-Locate With Other Radars and Radios • Can Be Covert
Resolution, Ranging & Ambiguities	• Small Dynamic Range	• High Process Gain • High Resolution • High Dynamic Range	• Higher Quality, Clear, Focused Images

TABLE 2. Relative Performance Comparison Between GP radar and UWB radar.0

In summary, while UWB imaging radar performs a similar function as conventional imaging radars used for ground penetration, it offers a performance level one or two orders of magnitude higher than conventional GPRs. While UWB radar has many technical advantages, the key benefits of these systems are as follows:

- **Higher Quality Data -** Not only is UWB radar data higher quality than conventional GPR technology, but it is sufficiently clean to be processed tomographically into three dimensional images.
- **Simplicity & Lower Cost. -** All of the electronic components are simple, low power and comparatively inexpensive. Processing requirements have been reduced.
- **Non-Interference -** UWB radar does not interfere with, not is interfered by , other radios, radars or other UWBT units.
- **Covert. -** Since the UWB radar transmissions are broadband, weak and very noise like, the system is covert. So much so, that at reasonable ranges the signals can not be intercepted or detected.

6. INVEST UWB Radar Evaluation Status

Assessment of UWB imaging capabilities and their utility and feasibility for INVEST is at an early stage. There are definite incentives identified for achieving the indicated dual-use of key communication and object registration functionalities. Actual proof of concept experiments and measurement of performance is dependent on progress with component hardware. Theoretical estimates and software simulation are the available choices for scoping practical application prospects, some of which have been provided in this initial paper.

Additional simulations more closely modeling the operational environment are planned in conjunction with related simulation of the UWB communication LAN. These efforts will parallel the component hardware development at Time Domain Corporation. Assuming continued positive simulation results, and resolution of the indicated processing challenges during FY 99, the plan is to assemble the imaging components and perform proof of concept testing in FY00 in the parameter range important to INVEST application goals. If concept testing indicates a viable dual use system is achievable, a vehicle mounted array will implemented and tested in FY 01.

Technology assessment efforts made in FY 98 indicate most radar imaging work is focused on ground penetrating systems. This includes US Army UWB impulse technology under development at Army Research Laboratory’s UWB Radar Program for use in mine field detection. The one exception is commercial development of a UWB imaging radar by Time Domain Corporation for application to law enforcement. This product will image through walls to improve officer safety for forcible entry situations.

Time Domain Corporation, inventor and principal developer of the UWB radio technology has agreed to work with STRICOM to provide an advanced prototype UWB radar array to support INVEST application evaluation. These units are forecast for initial proof of concept testing in FY00. The concept test data will provide a realistic basis for design and implementation of prototype array experiments in late FY00. Results of these efforts will feed into mobile platform integration and imaging experiments in FY 01.

7. Conclusions

Based on findings to date, a surrogate UWB imaging radar sensor appears capable of providing a real-time imaging and object registration capability with precision adequate for INVEST application. This should be feasible using an expanded set of equipment common to the UWB communication network. It is projected that this could be demonstrateable in an INVEST static configuration in FY 00 and potential mobile trials in FY 01 if commercial hardware component development and demand continues at it current pace.

Key issues which have not been addressed in adequate detail are:

- 2D vs 3D processing requirements
- Range/precision tradeoffs
- Mobility interactions
- Software and hardware configurations to support concurrent imaging and network communication components
- Vehicle integration for dual-use.

These are planned efforts for the on-going INVEST program. Technical feasibility is a first priority, and feasibility demonstarion will precede significant vehicle integration effort.

This will be addressed initially via simulation in the INVEST use context and evolve to equipment experiments when hardware components become available. Mobile dynamics testing will be used to finally assess the robustness of the image acquisition scheme and effectiveness of a low profile antenna configuration during pitch and roll on battlefield terrain prior to use in a field exercise.

8. Suggested Future Work

The INVEST program has a parallel charter to identify potential operational benefits deriving from its embedded simulation training development activity. In general these work areas will be beyond the scope of INVEST to pursue but are important to highlight for other programs or researchers to perhaps undertake and carry to a potential high-payoff conclusion.

The generic nature of a compact, low power, all weather, day/night, foliage penetrating, imaging sensor is intuitively of high value for military missions. If in addition it has highly covert position sensing that allows relative geo-location of other units and personnel within a centimeter, over kilometer ranges, even in urban areas where GPS systems fail, it deserves even further attention.

The US Army UWB radar mine detection and foliage penetration effort is an early example of the potential operational impact. Other clear benefits are apparent for operational telemedicine, perimeter defense, surveillance telemetry, logistics tracking, and military special operations. This is the nature of the UWB radar sensor being assessed for INVEST training application.

As this emerging radar and communication technology matures, it appears capable of dramatically extending, and enhancing situational awareness on the battlefield. That fact that this can be done without disturbing existing communications infrastructure, or alerting enemy surveillance and detection devices, is a powereful battlefield discriminator that should translate to a many-fold effective force multiplier for the operational US military.

Based on these preliminary observations it is recommended that UWB sensor and communication technology be broadly evaluated by all services and exploited through focused funding across multiple operational application areas.

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