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Author:	Ivan Cowie
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Through-Wall Surveillance for Locating Individuals Within Buildings

Final Scientific and Technical Report

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Ivan Cowie
Time Domain Corporation
330 Wynn drive, Suite 300
Huntsville, AL 35805
256-922-9229

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ABSTRACT

Law Enforcement personnel need a portable device that is able to sense individuals moving within buildings. Existing Ultra Wide Band (UWB) Radio-Wave radar technology cannot penetrate solid metal walls. Therefore, continuing the work from the study of sound through walls[1], Time Domain Corporation (TDC) developed an acoustic-sonar based motion sensor platform, which is able to sense motion of individuals through walls, including those made of metal. Adding TDC's previously developed UWB mono-static motion-sensing radar, which is based on TDC's existing radio hardware/software P210 device, enhanced this platform by being able to work through otherwise acoustically dead, non-metallic walls. The fusion of these two technologies provides sensing coverage that was previously unavailable than from either one alone. As a result of the new fused system, it should be possible to detect individuals in hiding behind walls or in shipping containers lessening the exposure of Law Enforcement personnel to danger.

1.0 SUMMARY

In an US Army SBIR phase one program, Time Domain Corporation (TDC) developed a sonar test-bed. Intended to be pressed on to a wall or support structure, the unit generates sounds by vibrating the wall in order to fill the subject room with sounds, then listens to a series of returns to find differences that result from motion inside the room. The basis for the science that allows the sonar to function is nearly identical to that which is currently used in TDC's UWB mono-static radar. TDC has previously proven and demonstrated the radar with its See Through The Wall (STTW) product offerings: RadarVision® and SoldierVision®. The goal of this project was to fuse the sonar and radar into a single test bed. TDC used its P210 UWB development platform as a smaller radar device towards accomplishing the goal. Since the UWB radar phenomenology is already proven, this report focuses more on the sonar research. Field tests showed the efficacy of the sonar approach.

In this NIJ Grant program, TDC modified its P210 mono-static radar and the sonar, integrating the two into a common portable and battery-powered unit. It should be noted that the initial phase of the proposed three-phase development approach was not selected or funded to be performed on this program. Three prototype systems were developed and delivered on this contract, along with this final technical report, user manual and referenced videos. This report relies on the reader to refer to the associated videos ("*phase-1-horse-trailer*, *phase-1-indoor* and *phase-2-indoor*") that show the development testing, configuration and final operation of the system.

While the prototype system was able to detect motion through walls using both radar and sonar, the sonar proved to be sensitive to motion on both sides of the wall. To overcome this challenge near term, the user can remove the display from the system and operate it remotely (as shown in the video "*phase-2-indoor*"). With further development it is believed that the challenges and issues described in this report can be overcome and result in a viable product.

2.0 INTRODUCTION

Law enforcement personnel routinely expose themselves to danger as they search buildings and containers to investigate incidents, clear inhabitants for safety, rescue hostages, or find perpetrators in hiding. Methods in use prior to this development currently include: gathering intelligence information, real-time surveillance, dogs, opening for visual inspection, and no-knock entry. A device that could sense motion through walls provides increased situational awareness, prior to entry, and thereby increases the safety of all the individuals in the area.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

Over the years, people have come to realize that a given room seems to have an acoustic 'signature', in that as sounds are being made in the room, it sounds differently (or reverberates) as objects in that room move around. If we can: (1) create/play a calibrated sound sequence into a room, (2) listen for and record that first response (call it echo1) to use as a reference, (3) pause long enough to be sure the sound has died down, (4) play the calibrated sound sequence again, (5) listen for and record that second response (call it echo2), (6) then process the two recorded echoes looking for differences between them, then we could theoretically detect that something in the room moved or changed (sounded different) between the two passes. If steps 3 through 6 are repeated in a continuous fashion, replacing echo2 with a fresh recording each pass, a continuous-time motion detector is realized. The concept easily extends itself to stimulating the room with sound and recording the response, through one of the room's own walls.

A data collection and analysis platform was constructed, to generate a complex sounds (using a PC computer), amplify and stimulate walls using a special speaker with sound energy, listen with a microphone, and digitize/analyze the sonic returns (using the same PC computer). Components of the analysis system shown in **Figure 1** essentially are:

- Sony VGN-UX390N Computer
- Included standard computer microphone
- Audio Amplifier HP 1286A
- FG-142A Force Generator (functions as a contact speaker) Labworks, Inc.

Pulse waveforms of differing bandwidths stimulate the speaker/wall, and digitized samples (single-channel, 44.1 kHz rate) are collected, producing a time/magnitude waveform.

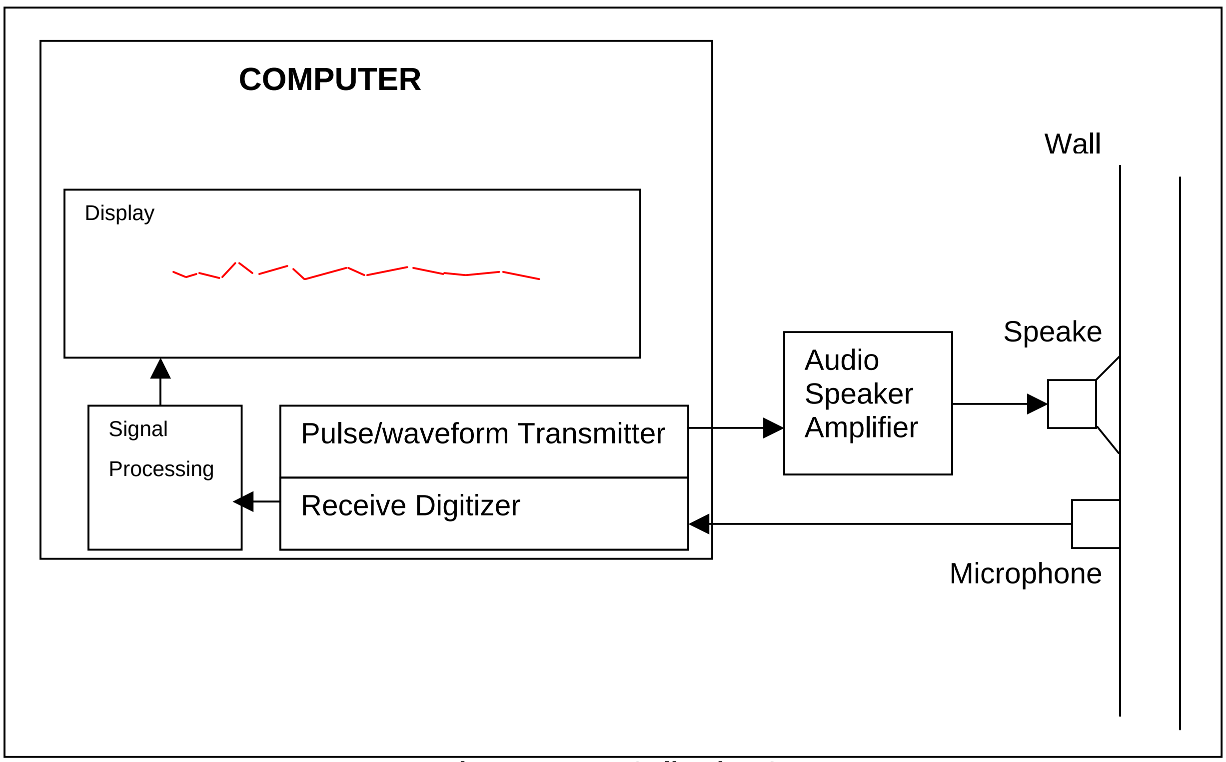

Figure 1: Data Collection System.

A waveform train consisting of ten pulses is generated and stored in the Pulse/waveform Transmitter section of the program, destined to be sent to the computer's audio sound output, on command. Although each pulse of the ten are identical, the pulse shape is designed to have sufficient bandwidth and time-length, so that each one by itself can fill the room and decay to nearly zero, before the next one begins. A time (horizontal, relative units) and magnitude (vertical axis, Analog counts) plot of the pulse is shown in **Figure 2**. The time delay is related to the distance from the sensor and the source of the reflection.

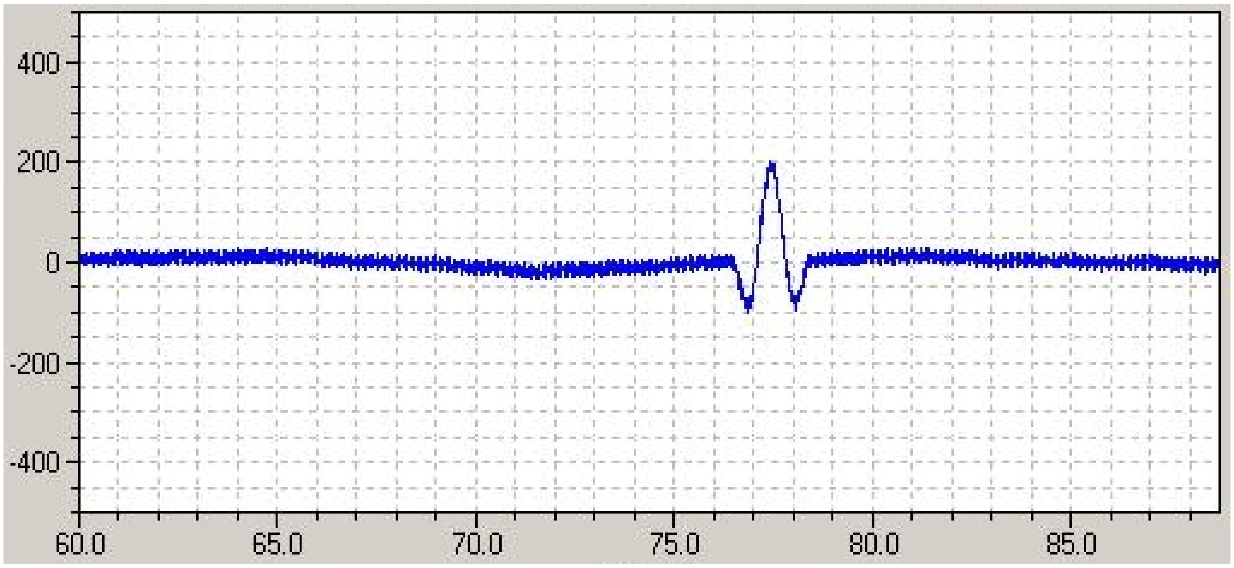

Figure 2: Example of Transmitted Sound Waveform (Amplitude vs. Relative Time Delay).

The short time duration of the pulse and the many frequencies that the pulse contains helps to penetrate the wall, as well as provide some echo characteristics that are beneficial for time-and-magnitude (waveform) processing. For example: (1) an object that is larger will reflect more sound than one that is smaller, and thus the return signal is greater (bigger on the display, and changes shape), (2) the closer an object is to the sensing wall, the earlier its echo returns (more to the left, earlier-time, changing the shape on the display), (3) an object's echo becomes smaller when moving away from the sensing wall, and larger approaching it (waveform changes shape on the display), (4) objects of differing materials reflect/absorb different frequencies (waveform changes shape on the display), and (5) objects with complex three-dimensional surface shapes contain components of all of the above, and therefore the echo is different for each aspect (facing angle) it presents (waveform changes shape on the display). Note the common thread, that in each case, the waveform presented changes shape for target movement – no Doppler or frequency-shift detection is required. For the cases where a room has a multitude of objects of varying complex shapes, materials, sizes, and positions, each room thus equipped has a unique ‘signature’ that results from the intricate superposition of the contribution of each in time, magnitude, and frequency components – including the ensemble of the various bounces across each other. In light of these characteristics, one simply observes the display, looking for changes as one of the objects moves or rotates. To make the changes more pronounced, a calibration pass of pulses are recorded, to be used as a reference waveform (see example, **Figure 3**); then, subsequent passes are filtered, subtracted point-by-point, and scaled to produce the display.

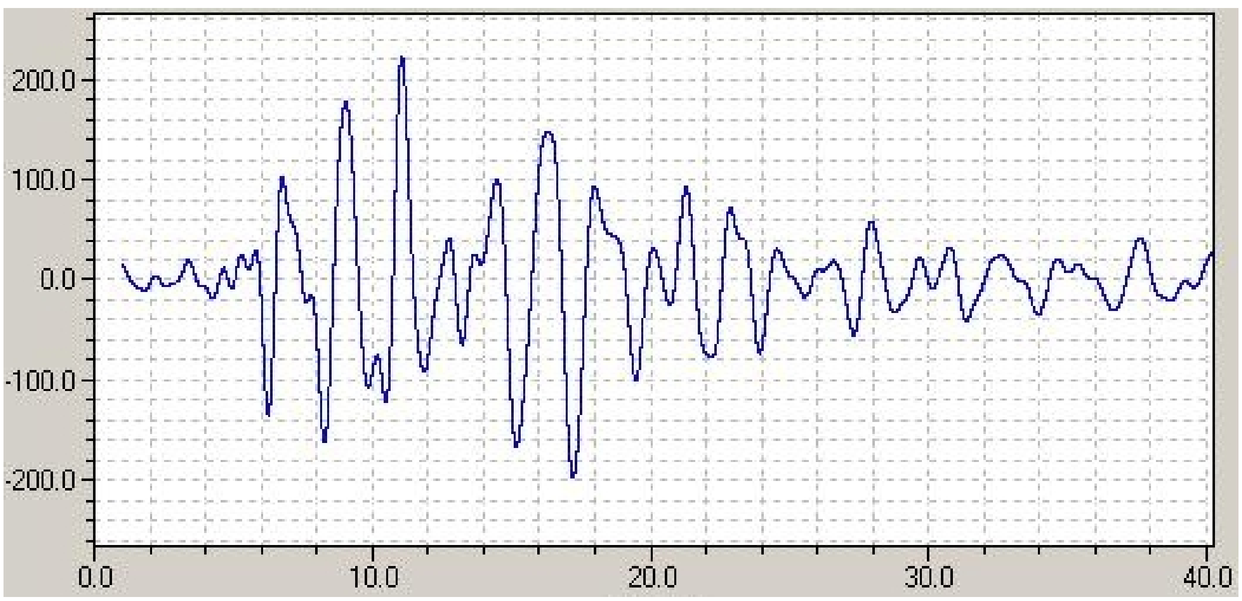

Figure 3: **Example Room Response, Reference Waveform, Before Subtraction.**

Ideally, a flat-line waveform would indicate a no-motion condition (see example, **Figure 4**) – due to the fact that both echoes were identical, since their subtraction (difference) was zero.

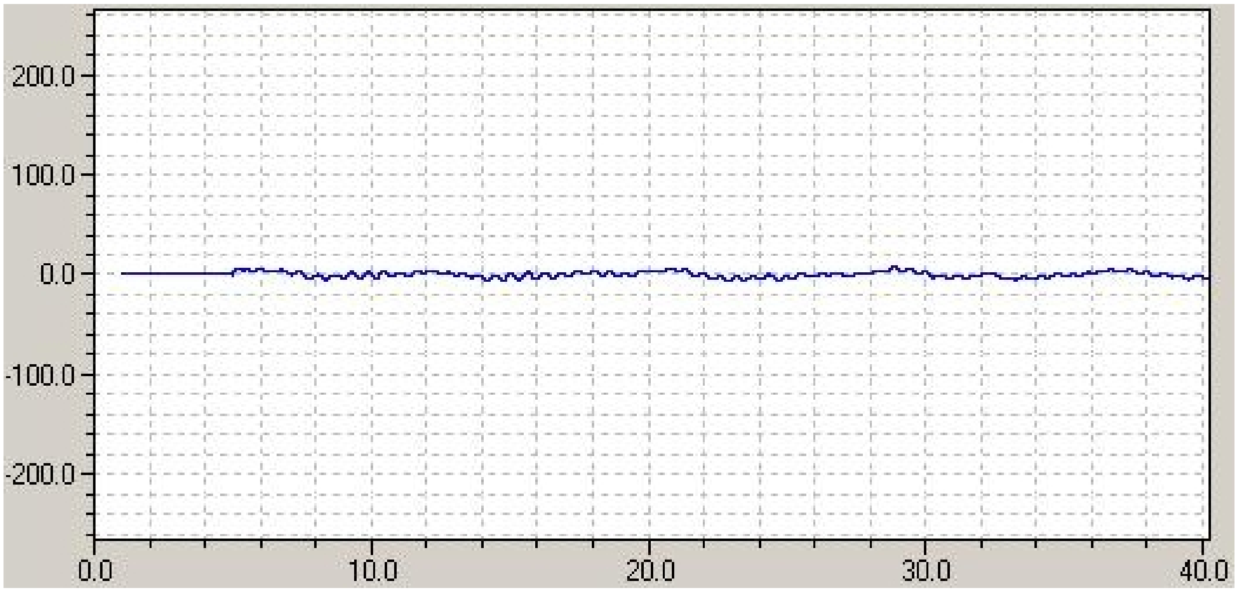

Figure 4: **Room Response, Targets and Clutter Stationary, After Subtraction.**

When one or more of the echoes changes as a result of being moved, the subtracted echo no longer is a straight line (see example, **Figure 5**).

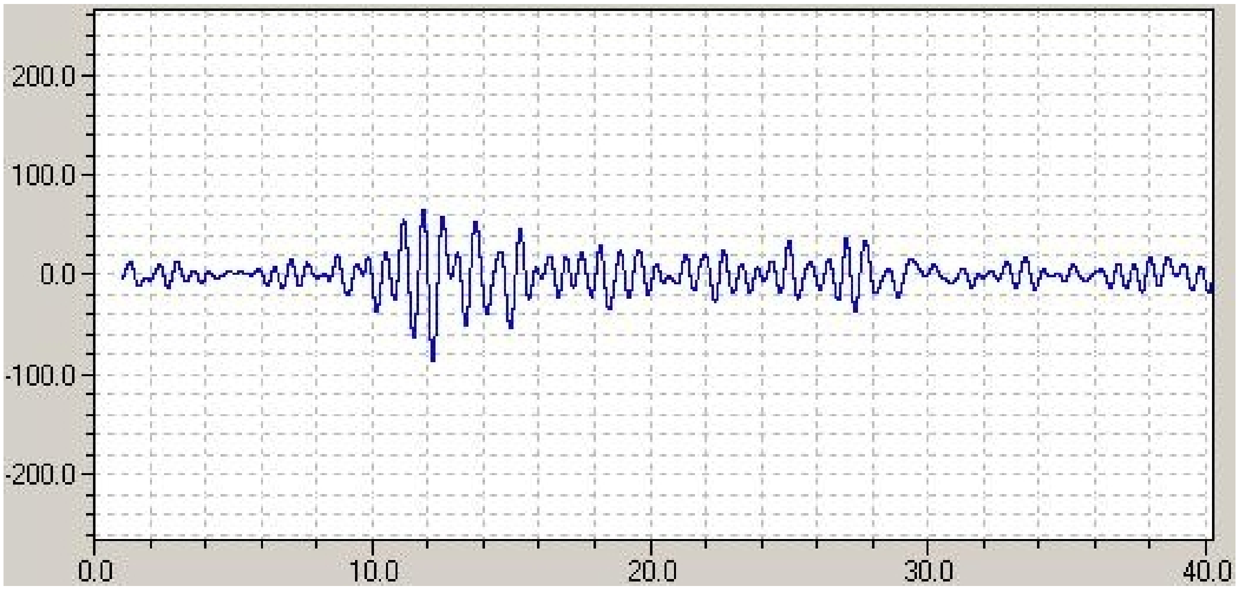

Figure 5: Example Room Response, After the Target Moved, After Subtraction.

The prior discussion focuses on interpretation of the waveforms. This helps to emphasize the physics behind the sensor. It also had the advantage that the operator's brain can pick out subtle clues, like how correlated the phase of the return or returns are to differentiate ambient signals or multiple targets. However, we are cognizant that this interface needs to be simplified to a simple red light/green light detection. Independent detection thresholds were set for both the radar and the sonar. These were then used to provide a display with three rectangles. The upper two rectangles correspond to the sonar. One is either black or white to indicate if the sonar is active. The other sonar rectangle is a detection indicator. When the sonar did not detect any targets, the box is green (see example, **Figure 6**). When it detects a target, it turns red (see example, **Figure 7**). If it is indeterminate, the rectangle is black. The lower rectangle is the radar's detection indicator. It uses a similar detection scheme, but has the added feature of displaying the range to the closest detection. This range measurement can be useful if the operator is concerned if the operator's own movements are causing false alarms

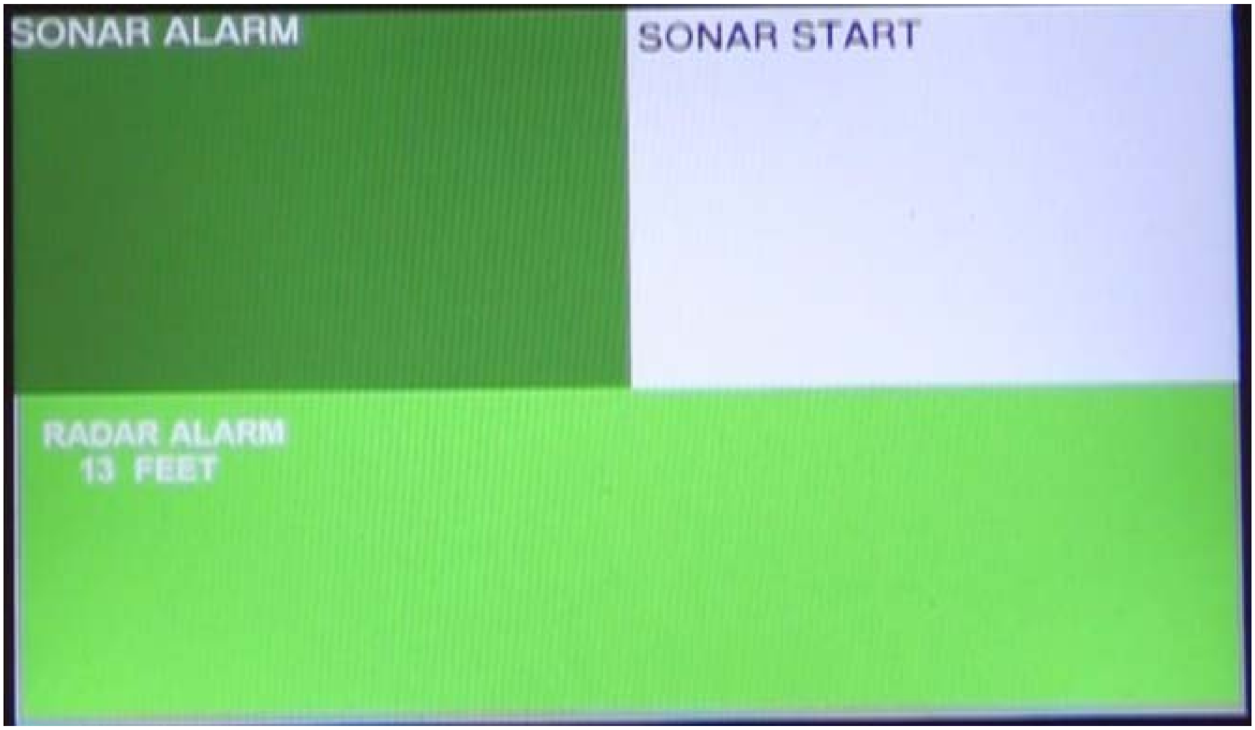

Figure 6: System Display – Indicating no motion detections.

As an enhancement, a latching action could be added to the display, for the cases where targets move, then go back to the same initial location (which would define a 'presence detection' mode – future enhancement). As time continues, new reference waveforms are created as the boxcar average of the last 20 waveforms (this is the 'motion mode', as delivered). Finally, an alarm threshold is assigned, so that the alarm's flashing box is displayed whenever the waveform's value crosses the threshold. To be able to reset the audio system quickly after repositioning against a wall, a reset box touch-screen control was added to the screen. As delivered, the radar and sonar engineering displays and adjustment parameter fields are hidden, and then replaced with flashing alarm boxes.

Figure 7: System Display – Indicating motion detections.

In phase two of the project, adjustments to the process priorities of the signal processing threads on the computer allowed the pause between sonic pulse bursts to be reduced, creating a faster and more continuous operational system.

Integration of the radar required mechanical modifications so that it would fit and work alongside the sonar, and so that it could operate on an external lithium battery. Software modifications to the radar included the addition of a *range-to-target* reading on the radar-alarm display.

Detection ranges for each system were completely dependent on the system placement and the environment/construction of the walls. The sonar could have no detections for masonry walls, and up to 22 feet for single metal walls. The radar could have as little as 3 feet and as much as 45 feet depending on the amount of shadow-causing metal in the target's path.

Videos were created for each phase of the project. Phase one videos were all without the radar, and the phase two video shows the radar and sonar combined. *Phase-1-horse-trailer.wmv* is the name of one of the videos in phase one, showing a person moving inside a converted horse trailer (metal walls). The top display is the raw time-domain pulse ensemble, and the bottom display shows the processed waveform. *Phase-1-indoor.wmv* shows a person moving inside a room. In this video, the potential for presence mode can be seen – even with the person motionless, the waveform is showing a continuous alarm condition (not a single flat line). Finally, the video named *phase-2-indoor.mpg* shows the final completed unit pressed against an interior wall and indicates alarm conditions as a person moves on the other side of the wall.

A photograph of the assembled combination of the radar and the sonar is shown in **Figure 8** and **Figure 9**.

Several challenges needed to be overcome. These challenges included the operating system issues, the interface between the acoustic transducers and the surface of the wall, the sonar's signal-to-noise ratio, sonar's dynamic range, and false alarms caused by the operator's movements.

Issues with respect to the operating system continually plagued the development. The operating system had a number of interrupts and would dynamically control which tasks were being executed that would violate timing constraints. This was particularly problematic in performing the signal processing in real-time without disrupting data collection in the sonar. A significant amount of time was spent addressing these timing issues. These issues had to be resolved prior to displaying the radar and sonar data simultaneously.

The sonar is extraordinarily sensitive to the pressure applied to the wall it is in contact with, as well as the pressure the transmitter's transducer and receiver's microphone applies to the wall. This becomes quite significant if there are bumps or ridges in the wall. This was mitigated by using the Force Generator to directly stimulate the wall, and by designing a contact tensioner. Simply put, the contact tensioner is spring loading for the acoustic transducers that compresses when the device is engaged against the wall.

The sonar's signal-to-noise ratio started too low. The noise floor is defined by several things, but was generally dominated by environmental noise, particularly man-made noise. A significant portion of this noise came from personnel movements within the building, in a room outside of the test area. This was mitigated in two different ways. The random noise was mitigated by integration. The more coherent noise signals were mitigated to some extent by the more careful selection of the shape/characteristic of the transmitted pulses, making them unique compared to the interfering sounds (this resulted in the waveform of **Figure 2**).

On a related note, we also had to improve the sonar's dynamic range. The dynamic range is the ratio of the largest signal that can be measured to the noise floor. Analysis of the environments involved provided insight into the frequency/time content of echoes or reflections[1]. Using this data, frequency filters were synthesized and added to the signal processing, which enhanced the near/far and strong/quiet performance and also rejected the out-of-band signal content.

The last challenge (and not yet completely solved) is the extreme sensitivity of the unit to motion of the operator, and/or the motion of objects on the operator's side of the wall. This is also true of the radar, though to a lesser extent. The advantage of the radar is that its directional antenna leaves the dominant effect being reflection from the wall structure. The sonar, on the other hand, actually excites the wall, which excites signals on both sides of the wall. This was mitigated by remoting the display from the sensor unit. The Palmtop made this adaptation very easy.

Note: a system configured and implemented as described (with a fixed, learned reference instead) could be considered a 'presence' or 'field disturbance' detector, since the alarm-output condition persists until the target [or target ensemble] moves back into the exact position it [or each one individually] had at the time the reference waveform was created. In the specific case where a room is known to not contain any targets of interest and a reference waveform is captured (learned), then presence detection is enabled (future enhancement). Other systems classified as motion detectors (including this one in its present embodiment), only produce an alarm output while targets are actually moving, with no capability to detect that the target has moved back into position or left the field.

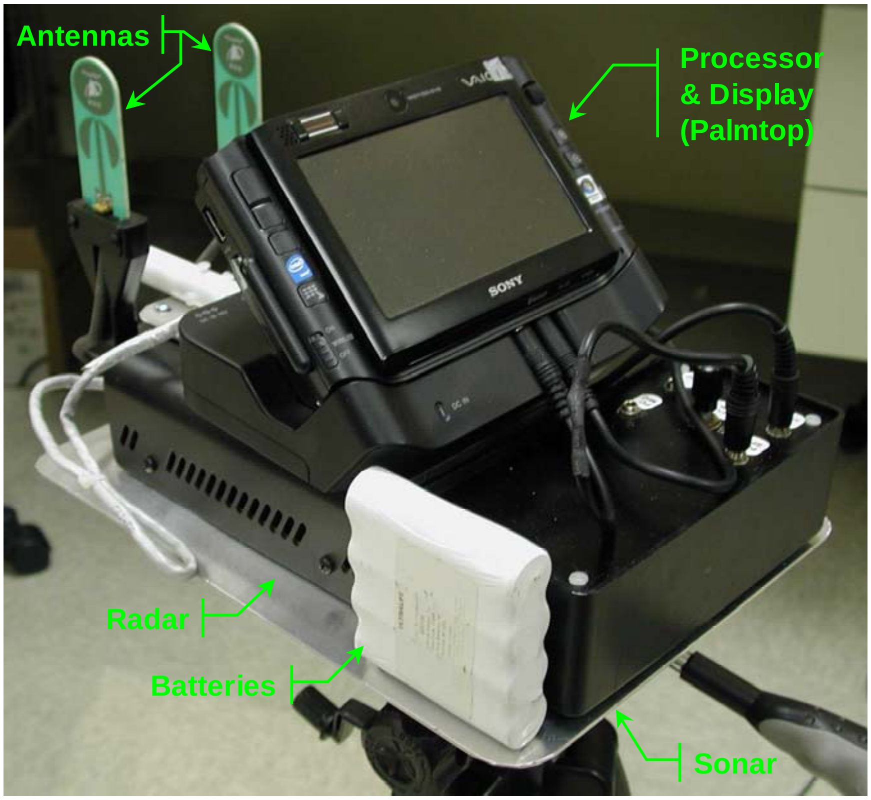

Figure 8: Photograph of Back of Assembled Unit, Sonar and Radar.

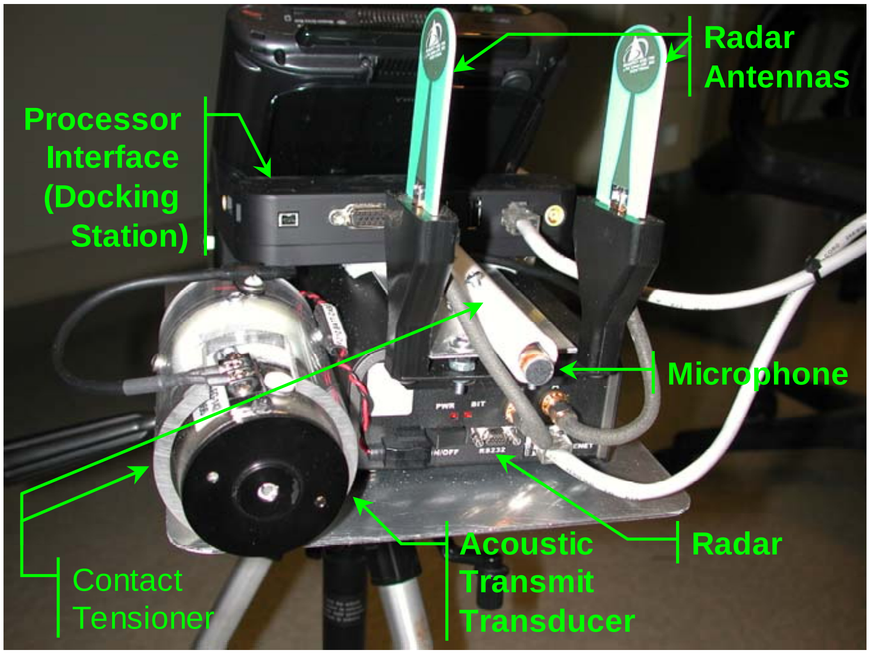

Figure 9: Photograph of Front of Assembled Unit, Sonar and Radar.

4.0 CONCLUSION

Results indicate the feasibility to detect persons moving behind metal walls in the case of the sonar, and behind non-metallic walls in the case of both the sonar and the radar. Greater sensitivity both in range and in alarm confidence is achieved for quiet, isolated and stationary environments, and for situations where the operator is as still as possible and there is no motion on the operator's side of the wall. Available battery power and power-handling capability of the Force Generator (speaker), basically limits the unit's sonic performance to walls other than brick and concrete. By replacing the Force Generator with a conventional speaker and placing the unit out from all obstructions and walls (line of sight operation), it appears to be sensitive enough to detect breathing for some orientations of the target body, for both the radar's operation and for the sonar's operation. However, a speaker-based sonar will reflect so much energy off of the wall that the display will have to be remote to mitigate false alarms from the operator's movements.

5.0 RECOMMENDATIONS

For future development, define a more formal test program to demonstrate reliability and repeatability. The test program might include: 1) Operators (other than the developers) test the system in a variety of scenarios, 2) Collect results for performance/confidence analysis and 3) provided feedback on usability, setup, difficulties, etc. Areas for future research towards productizing include:

Sonar: with further algorithm development and the addition of several more microphones, it should be possible to improve the sonar unit's man-made sound rejection capability, reduce the false-alarm rate caused by excess sensitivity to pressure applied to the wall, increase the detection range, and add the 'presence detection' capability as a user selectable option.

Radar: addition of a back-reflecting assembly over the antennas and a radar dome to protect the antennas from direct water contact. A filter algorithm could be added to the range display, removing some of the reading jitter, thus making it possible to track a target somewhat, via a more accurate rate-of-closure measure.

APPENDIX A: ACRONYMS

DPD – Dallas Police Department

KHz - kilohertz (1,000 Hertz, or cycles)

NIJ – National Institute of Justice

PC - Personal Computer

P210 - The model number of Time Domain's development UWB radio

RADAR - Radio Detection And Ranging

SBIR - Small Business Innovative Research

SONAR - Sound Navigation And Ranging

STTW – See Through The Wall

TDC – Time Domain Corporation

UWB - Ultra Wide Band

REFERENCES

1. SBIR Final Report, Phase One, for topic A-03-056, U. S. Army Research Office, report CLIN 0001AF (410-0109), 08/06/2004.