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HAND-HELD ULTRASONIC THROUGH-THE-WALL MONITORING OF STATIONARY AND MOVING PEOPLE

Jaycor

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13. ABSTRACT *(Maximum 200 Words)*
A prototype system for monitoring respiration and movement through metallic and non-metallic walls has been developed and demonstrated. The man-portable sensor uses high energy ultrasonic pulses and ultra low noise amplification of the return pulse echoes to detect the breathing or motion of individuals in an enclosed space. A real-time video display on the hand-held transducer assembly provides the user with a measure of the location of the detected motion to within one-foot accuracy, out to a maximum range of thirty feet. Pulse forming circuitry, data acquisition and processing electronics, and battery power are stowed in a backpack. The sensor was designed to penetrate through a variety of wall materials and configurations; however, a limitation exists on its ability to penetrate through multi-layer wall configurations, such as are commonly found in residential and commercial buildings, where a significant air gap might exist between the inner and outer wall layers. Potential applications for this sensor include search and rescue, law enforcement, and vehicle and container inspection.

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This final report serves to document the accomplishments of the Ultrasonic Through-the-Wall Surveillance Program (F30602-00-C-0196) co-sponsored by the Air Force Research Laboratory (AFRL) and the National Institute of Justice (NIJ). The principle investigator was Dr. Norbert Wild. This effort was the first government-sponsored program to investigate the use of ultrasound as a means of TWS (Through-the-Wall Surveillance). We would like to thank Mr. David Ferris of AFRL at Rome, NY who was the program technical manager and provided assistance and guidance throughout the course of this effort.

At Jaycor/Titan's San Diego facility, Frank Doft and Steve Niederhaus were responsible for most of the laboratory testing. Mr. Niederhaus directed the manufacture and assembly of the brassboard prototype portable sensor. Hon Lam was instrumental in laying out the electrical schematics, breadboarding the various subcircuits, and troubleshooting the assembled circuitry. Chris Lum was responsible for the fabrication of the plastic molded parts and other mechanical assemblies. Greg Niederhaus was instrumental in finding a vendor to modify the back-pack assembly and also assisted greatly in the fabrication of mechanical parts and mounting fixtures. Lastly, John Wondra provided the expertise in implementing the software algorithms and operator interface.

LIST OF ABBREVIATIONS AND ACRONYMS

AFRL	Air Force Research Laboratory
COTS	commercial off-the-shelf
EMI	electromagnetic interference
FPED	Force Protection Equipment Demonstration
LE	law enforcement
NIJ	National Institute of Justice
PHSM	Prisoner Health Status Monitor
PRF	pulse repetition frequency
SLA	stereo-lithographic apparatus
SPIE	The International Society for Optical Engineering
SWAT	Special Weapons and Tactics
TWS	Through-the-Wall Surveillance

EXECUTIVE SUMMARY

The Ultrasonic Through-the-Wall Surveillance (TWS) Program (F30602-00-C-0196) was awarded to Jaycor on 21 August 2000. Technical work on the contract was completed on 28 February 2003. A man-portable ultrasonic TWS system prototype was designed, built and tested under the effort and will be made available for demonstration and evaluation purposes.

The National Institute of Justice (NIJ) and the Air Force Research Laboratory (AFRL) initiated the program in response to the need for a TWS system that would be capable of detecting and locating moving or stationary individuals behind either non-metallic or metallic wall types. Some of the primary applications of this sensor will be to determine the presence of any individuals in enclosed spaces under law enforcement (LE) Special Weapons and Tactics (SWAT) scenarios or in civilian search and rescue operations. Additional applications include its use by U.S. Customs agents for inspection of vehicles and shipping containers at border points of entry.

Under an initial Jaycor IR&D effort, the concept for a TWS monitor capable of detecting mm-scale respiratory motion through a wall was demonstrated to AFRL and NIJ representatives. This effort was then focused on developing that concept into a lightweight, hand-held TWS monitor to enable accurate location of stationary and moving individuals. The brassboard prototype developed under this effort is capable of detecting a stationary individual behind a single layer wall out to a distance of 25 feet and can detect moving individuals out to 30 feet. Note that the sensor head is required to be in intimate contact with the wall surface; i.e., there is no stand-off capability associated with ultrasonic detection. This is explained in Section 1 as due to the large acoustic impedance mismatch that exists between a solid/air interface.

The program consisted of an initial phase of testing and development of a breadboard system, followed by a second phase of design, additional testing, fabrication and assembly of the prototype brassboard system. A number of formal presentations were made at the annual AFRL/NIJ Program Reviews held during the course of the effort, as well as at the International Society for Optical Engineering (SPIE) Conference on Enabling Technologies for LE held November, 2000 in Boston, Massachusetts, and the SPIE Aerosense 2002 Conference held in May, 2002 in Orlando, Florida. A demonstration booth was also set up at the Force Protection

Equipment Demonstration (FPED III) held at the Marine Corps Base in Quantico, VA in May, 2001. Figure 1 highlights the program's activities during the course of the effort. Figure 2 shows a photograph of the hand-held prototype TWS sensor, as developed under this effort, being demonstrated on a solid wood door. The sensor is attached via a 5-foot umbilical cord to a backpack that contains the associated send and receive electronics and battery power supply. Figure 3 shows a close-up of the video display unit during operation. Details of the user-controlled sensor functions and interpretation of the display are contained in the body of this report.

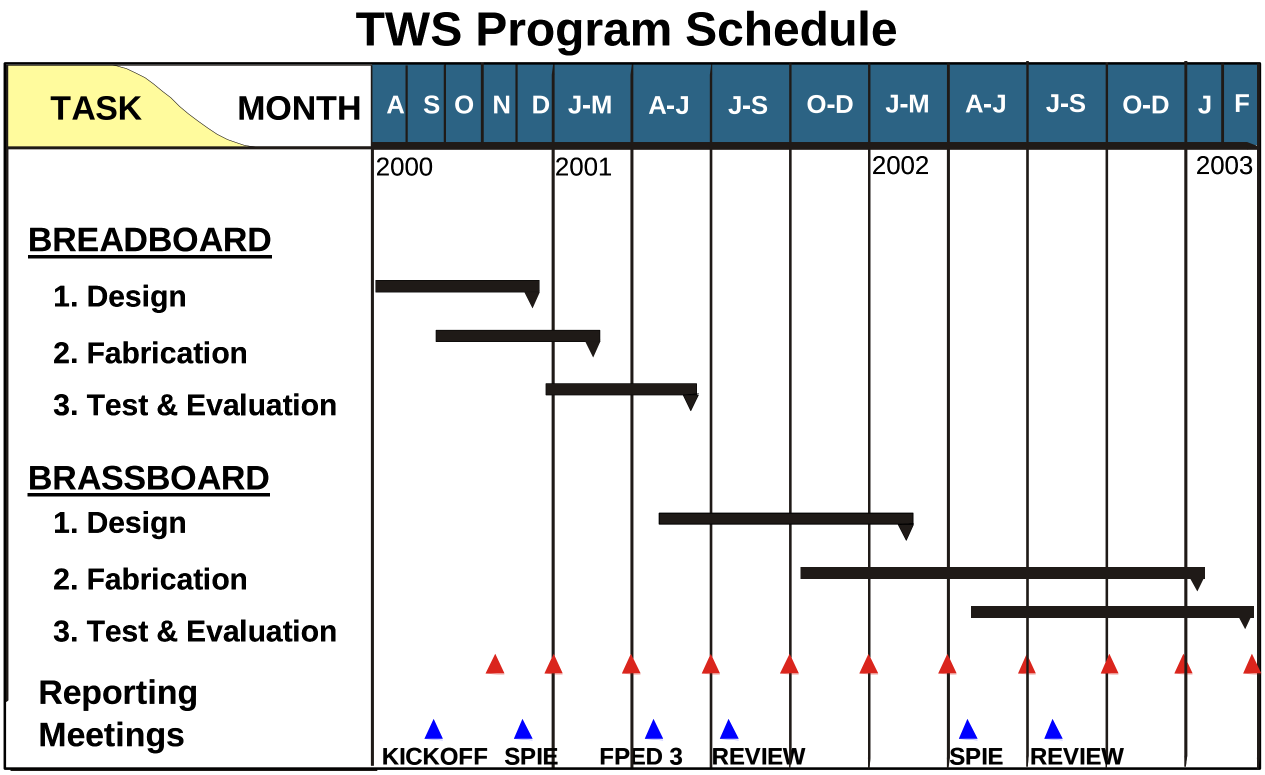

Figure 1. Summary of program activities.

Figure 2. Photograph of TWS prototype system being demonstrated on a solid wood door.

Figure 3. Close-up photograph of the prototype handheld display unit during operation.

1.0 INTRODUCTION

The goal of the TWS program is to demonstrate that a low-cost ultrasonic monitor, in contact with an outer wall of a room, can detect and locate multiple stationary and moving individuals inside the room, and can do so on a single, easily understood display. The ability to detect, locate and track people behind a wall would be of great value to LE and security personnel for counterterrorism, drug enforcement, and for some military and special operations applications [Ref. 1 to 3]. Example LE applications include hostage situations, SWAT-team scenarios, and vehicle inspections at international points of entry. A reliable TWS capability could provide critical life-saving information, particularly in situations where LE personnel must enter rooms that may harbor armed and dangerous criminals.

As a result of this effort, we have found that the detection of stationary people poses a greater challenge than detecting moving people. Meeting this challenge is essential, however, for TWS to support military and civilian counterterrorism efforts for which hostages may be unconscious or otherwise immobile. Overlooking a stationary person could mean the difference between life and death for that hostage.

The prototype system developed under this effort uses a high peak-power ultrasonic transducer operating at 30 kHz to transmit and receive short acoustic pulses. The transmittance of the ultrasound energy through a variety of wall and window materials including wood, metal, drywall, concrete, glass, composites and multi-layer wall configurations was measured and quantified. The prototype system employs signal processing techniques similar to those being developed concurrently for Jaycor’s Prisoner Health Status Monitor (PHSM). These algorithms allow for the determination of an individual’s respiration rate and, in some instances, heart rate. The TWS sensor focuses on detecting respiration since breathing is a reliable indicator of the presence of stationary as well as moving people. The prototype demonstration unit uses a single transducer for send and receive functions and can determine the location of a detected individual as a function of range from the transducer. Using multiple transducers, the individual’s two-dimensional spatial location inside the enclosure can also be determined using simple time-of-flight triangulation.

The advantages that an ultrasonic-based monitor might have over other TWS technologies; e.g., radar, include:

- Lower cost and lighter weight
- The ability to “see” through metal-lined walls and cargo containers
- An improved ability to locate stationary people, once detected
- Relative freedom from FCC regulatory constraints on radiated emissions
- Greater safety and acceptance, both real and perceived [Ref. 4, 5]

1.1 Through-the-Wall Surveillance Sensor Concept

The prototype TWS monitor that was developed under this effort was based on the previously demonstrated concept of using a piezoceramic transducer element to detect the respiratory motion of an individual behind a solid wall. A photograph of one of these commercially available (Airmar Technology Corp.) transducers is shown in Figure 4.

Figure 4. Commercially available Airmar AR-41 transducer with Jaycor’s custom circumferential copper ground shield for low noise operation.

Figure 5 shows the configuration we used in an early Jaycor IR&D program for calibrated measurements of detection of mm-scale motion through a wall. The respiration of a stationary person was simulated by a subwoofer speaker diaphragm with a maximum displacement amplitude of 1 mm (2-mm total displacement). The diaphragm was electrically driven to oscillate at about 1 Hz. The subwoofer, in its casing, was mounted on a table about 4 feet from the wall. The wall was a 1-by-8 board of solid pine wood (actual thickness 3/4”). Two Airmar AT-41 transducers (nominally tuned to 41 kHz) were stuck to the wall by Redux gel. The gel was sticky enough to support the half-pound weight of each transducer on the vertical wall without any other means of attachment. One transducer produced the ultrasound pulses, and the other received the return signal. Short (12 to 13 cycle) pulse trains were generated and amplified at 41 kHz. The pulse duration was 400 μs and repetitively pulsed at frequencies up to 20 Hz. Details of the results from this early IR&D test were published in the first of two SPIE journal articles generated under this effort [Ref. 6]. The successful demonstration of the ability to detect, through metallic or non-metallic solid materials, the respiration of an individual was the key to the development of a prototype demonstration unit as developed under this effort.

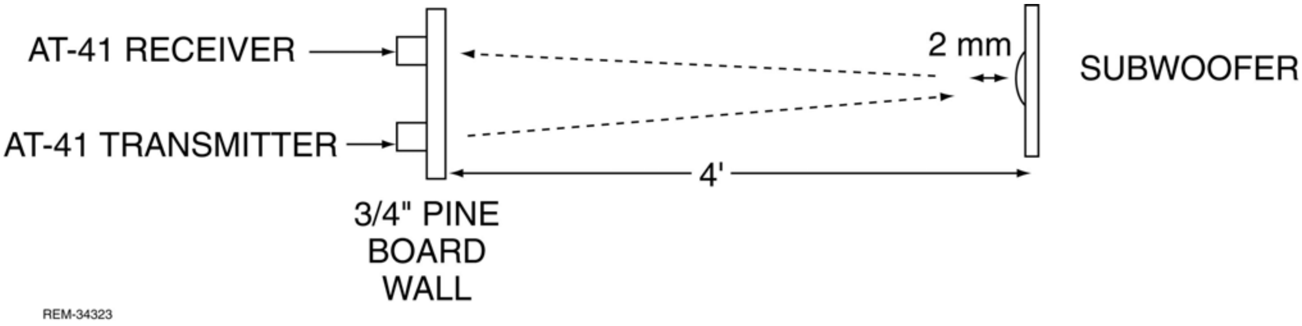

Figure 5. Configuration of Jaycor’s early demonstration of TWS of mm-scale motion.

The main technical challenges for ultrasound TWS are: 1) detection of the extremely weak return pulse echo, and 2) development of the signal processing software to confirm the presence of respiration. Due to the large acoustic impedance mismatch at any air/solid interface, very little ultrasound energy is projected into a room through a solid wall and, subsequently, very little of the return echo is passed through the wall back to the receiver. The acoustic impedance Z of a material is defined as

$$Z = \rho c, \tag{1}$$

where ρ is the density of the medium and c is the velocity of sound in that medium. The MKS units of Z are “rayls.” The standard value for air is Z_{air} = 315 rayls, while for most solids, Z ranges from about 10^6 to 10^7 rayls. In traversing between two different media, one can show [Ref. 7] that the sound power transmission coefficient, α_t, is related to the respective impedances as

$$\alpha_t = 4 Z_1 Z_2/(Z_1+Z_2)^2. \tag{2}$$

Thus, for an air/wood interface where Z_{wood} is on the order of 10^6 rayls, α_t is about 0.0013. This corresponds to a decrease in intensity level of 10 log (0.0013) = -29 dB. Thus, under optimum conditions, one can expect the return pulse echo to be down about -60 dB from the transmit pulse intensity after passing through the wood twice. To detect these relatively low amplitude return signals, we designed and fabricated a high-gain (>60 dB) active bandpass filter ($\Delta f/f < 5\%$) which can accommodate very small signal levels. In addition, a high power, low duty cycle, pulser was designed to efficiently drive the ultrasonic transducer elements at their maximum capability.

By utilizing this very sensitive high-gain amplifier, the detection of respiration is accomplished by measuring the time-varying phase shift of the acoustic wave’s return echo relative to the transmit pulse. Return echoes are received from virtually every hard object in the room at different times corresponding to their relative time-of-flight from the transducer. However, for motionless objects; e.g., desks, walls, etc., these phase differences have no time-varying component and can be rejected during the signal processing. Only those echoes that show a time-varying phase shift are recognized as potential indicators of respiration. These signals are then further processed for discrimination, location, and tracking. An algorithm for detecting and monitoring the respiration of an individual, and then determining his location in two-dimensional space, was developed under this effort and implemented as part of the brassboard prototype system.

2.0 METHODS, ASSUMPTIONS AND PROCEDURES

As shown in the program schedule (Figure 1), the effort was roughly divided into two separate phases. The first phase consisted of the design and development of a breadboard sensor. A series of laboratory tests and evaluations of various aspects of the breadboard TWS sensor were made. This phase culminated in the successful demonstration of the breadboard unit. The second phase was focused on developing a prototype brassboard demonstration unit. The design goal of the brassboard unit was to make the breadboard sensor hand-held and man-portable. Particular emphasis was made with regards to reducing the size and weight of the various electronic components. These included the desktop computer (replaced by a laptop computer), the high voltage pulser, the ultrasound wavetrain generator, the analog to digital converter circuit, and the video display unit. Fabrication, assembly and calibration of the prototype brassboard unit was completed during the last 3 months of the effort. This section of the Final Report will describe the various design features and how they were evaluated in the laboratory. A description of the fabrication and assembly procedures that were employed will also be given here. The results of the laboratory testing of the breadboard and brassboard prototypes will be presented in the following “Results and Discussion” section.

2.1 Breadboard Design Features

The breadboard demonstration system consisted of the following components: 1) IBM desktop PC, 2) National Instruments PCI-6110E 12-bit analog-to-digital converter board and interface box, 3) two Hewlett-Packard 8116A function generators, 4) Airmar developer’s kit high voltage pulse generator, 5) two Airmar AT-41 transducers, 6) two Jaycor high-gain tuned receiver amplifiers, 7) Jaycor data acquisition, processing, and display software, and 8) various signal and power cables. A block diagram of the breadboard system is shown in Figure 6. Note that items 1 to 4 and 7 required 110VAC wall-power for operation. One objective of the subsequent brassboard design was to eliminate these power requirements in favor of battery operation. The total weight of all the breadboard components was 120 lbs.

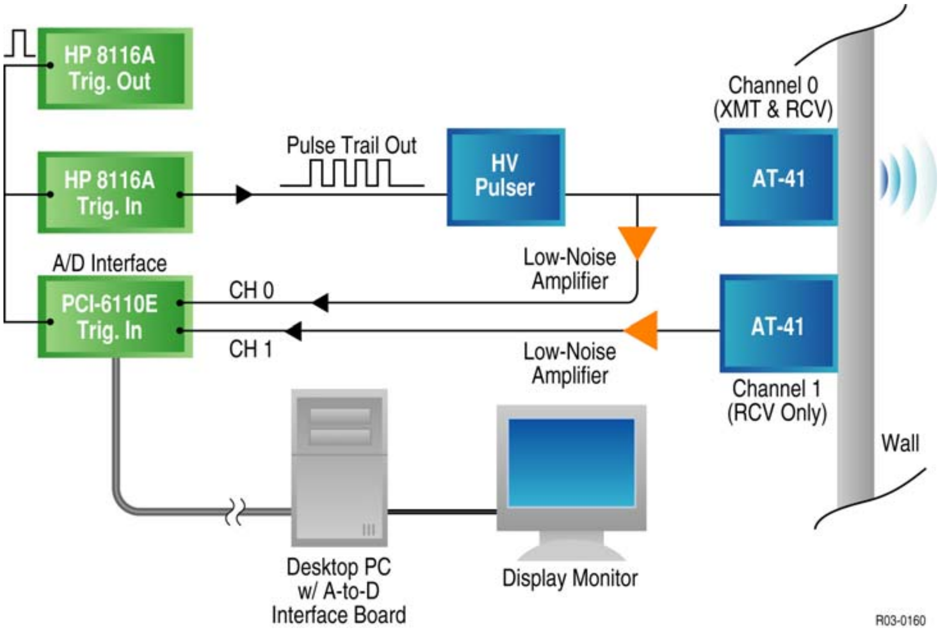

Figure 6. Block diagram of the breadboard TWS system.

The desktop PC that was used with the breadboard system served several functions; i.e., data acquisition control, data processing, and display (and storage) of the processed data. The two HP function generators functioned as a master trigger generator that initiated the transmit ultrasound waveform (typically a 10-Hz single TTL-level pulse, 10-µs wide), and a gated generator that would deliver the required number of TTL-level cycles to the high voltage pulse generator. The master trigger generator was also used to synchronize the A/D data acquisition sequence. The synchronized timing allowed for time-of-flight calculations (to determine the distance of any detected motion signal) and also enabled the various processing algorithms to occur on a reproducible and consistent basis.

The high voltage pulse generator consisted of a high voltage charging circuit, a high voltage MOSFET switch and a high voltage step-up transformer. The output of this transformer was then fed directly to the Airmar AT-41 transmit transducer using an in-line impedance matching power resistor (470 Ω). Received signals on the two AT-41 transducers (channels 0 and 1) were monitored using low noise, high-gain (30,000) tuned amplifiers designed and fabricated by Jaycor. Voltage limiters were used on the transmit transducer (channel 0) to allow for simultaneous transmission of 2,500-V drive pulses and the detection of 10-µV return echoes.

The analog-to-digital data acquisition system was bought from a commercial vendor (National Instruments) and consisted of a PCI-6110E board, a BNC-2110 interface box and a 2-meter connecting cable. The PCI board was installed in the desktop computer and was capable of sampling up to 5 M samples/sec simultaneously on two channels. Sampling software provided with the A/D board was then modified to incorporate our custom data processing algorithms and display software.

For the breadboard TWS monitor, the baseline approach was to use two identical commercial off-the-shelf (COTS) resonant transducers of the solid cylindrical piezoelectric type. One transducer transmits an ultrasonic waveform, and both transducers receive the reflected waveform. From the measured time-of-flight, the range of each person to each transducer can be found and, from triangulation of the two received signals, the two-dimensional location of each person is then determined. Both 30 and 41 kHz transducers (Airmar models AT-30 and AT-41) were used in the breadboard sensor to determine their effectiveness in transiting through various wall material types. These transducers have been modified with continuous electromagnetic interference (EMI) shields to allow for ultra-low noise signal reception.

The breadboard system was designed to operate in near real time using a high speed PC with a dedicated math co-processor to acquire and process the two received waveforms. The transducers were typically pulsed at a repetition rate of 10 to 20 Hz. The received signals were sampled and stored in the PC’s on-board RAM for quick processing. To illustrate the general idea behind the principal of motion detection, typical received and processed waveforms are shown in Figure 7. These signals are for a configuration where a solid piece of wood was placed in front of the transmit and receive transducers and a person was either absent or present several meters away on the other side of the “wall.” Two successive waveforms are shown for each case and the digitally processed difference signal is shown at the bottom of the figure. With no person present, the difference signal is relatively flat; whereas, with the presence of a person (breathing regularly), a quite noticeable time-varying difference signal is observed. This difference signal is the key to the detection and location of people when using ultrasound TWS.

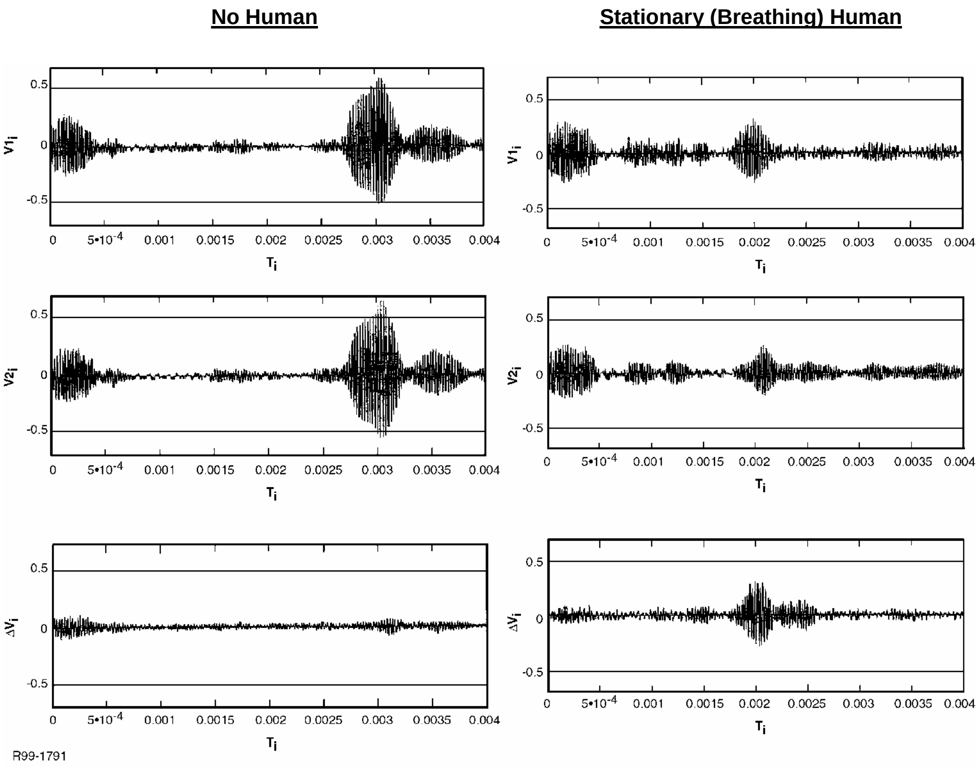

Figure 7. **Plot of two separate transducer signals and the processed difference waveform that can indicate the presence of a person breathing.**

As discussed in Section 1, the main sources of energy loss for TWS are in the air-wall transmission interface and in simple $1/r^2$ divergence effects. For long ranges (>10 m), air absorption can also become a factor in limiting detectability. Even with high losses at wall interfaces, and operating orders-of-magnitude below peak power, we showed that mm-scale motion through a 1.75”-thick layered wooden door using COTS transducers is detectable. Nevertheless, it is important to minimize the number of interfaces through which the ultrasound must pass. For this reason, it is necessary to closely couple the ultrasound source to the outer wall; therefore, we do not consider the ultrasonic TWS monitor to have any remote standoff capability. Also, due to the high losses at air-wall interfaces, the monitor can not see through a second interior wall.

We achieve close coupling of the transducers to the wall by applying a gelatinous cream to the flat front surface of the ceramic transducers and then pressing the faces of the transducers against the outer wall. The cream produces a very close coupling, boosting the return signal by order-of-magnitude. Our measurements indicate that virtually none of the wall losses occur at the interface of the outer wall with the cream-covered transducer face, and that virtually all losses occur at the inner wall/air interface. As will be discussed in Section 3, during the design and testing of the brassboard system, we found that a certain type of urethane rubber allowed for relatively good coupling (about a factor of 2 below that attainable using a gel). This rubber, about 1/16”-thick, is now an optional interface for the brassboard prototype system for applications where a gel would not be acceptable.

To detect the very small amplitude return echoes, a high-gain, active band-pass filter is used to increase the received signal to a level that standard data acquisition hardware can then acquire. The acquired waveforms are then stored in the PC’s on-board RAM for subsequent processing. The amplifier/filter combination does an excellent job of suppressing noise outside the amplified bandwidth (about 2 kHz).

The duration of each ultrasonic transmit pulse is tailored to the ring-up time of the transducers, which is about 100 to 300 μs (about 4 to 12 wave periods). For accurate determination of respiration, we have found that the pulse repetition frequency (PRF) needs to be about 5 to 10 pulses per respiration period. For respiration conditions ranging from sleeping to hyperventilating, respiration periods might range from about 10 to 0.5 sec, and adequate PRFs from 1 to 20 Hz. The duty cycle of the pulsed ultrasonic monitor, therefore, will never need to be greater than about 0.5%.

As mentioned above, in simplest form, the signal processing looks for differences between successive signals. Thus, by adjusting the time between successive pulses to allow for a substantial phase difference to occur in the respiration cycle, one can optimize this difference. In normal operation, the breadboard sensor sets an initial PRF of 10 Hz and then the averaging time and offset are adjusted to optimize the display. This differs from the brassboard system where the PRF and averaging times are fixed (about 10 Hz and 2 sec, respectively) and the only user adjustment is in the threshold for detection/display.

The breadboard system was demonstrated to be capable of locating stationary people and tracking moving people by two-dimensional triangulation of time-of-flight measurements. Time-of-flight measurements are easily made with ultrasound, as each foot of distance represents about a 1-ms propagation time, as compared to a 1-ns delay for radar. In the breadboard system, multiple people appear as separate pulse envelopes on the time axis, corresponding to different ranges to each of the transducers. This assumes, of course, that there is enough spatial separation between the people to allow for temporal discrimination. From the changing appearance of the pulse envelopes at the data refresh rate (ultrasound PRF), it is relatively straightforward to correlate separate people on each of the receive channels and then triangulate to find the locations of each. As will be discussed in Section 3, for the brassboard system, a single transducer is used, which provides for range information but does not give unambiguous spatial location (only to the extent that the detected person is within the cone angle of the transmitted ultrasound beam).

2.2 Brassboard Design Features

After successfully demonstrating the breadboard TWS system ahead of schedule, the second phase of the effort was initiated to build a hand-held, man-portable brassboard prototype TWS system. Rather than designing and building a custom processor and display system, it was determined that the desktop computer and data acquisition interface, and the I/O board in the breadboard system would be replaced with a lightweight, commercially available laptop computer and a stand-alone COTS A/D system. Due to the high data I/O rates (for both acquisition and subsequent real-time display) used in the breadboard system, a high performance laptop (Dell 8200 Inspiron) and A/D system (National Instruments DAQPad-6070E) were selected that were both capable of high speed data transfer using a FireWire interface (IEEE 1394).

The goal of a hand-held device meant that the data acquisition and computing hardware, as well as the associated transmit and receive pulser and signal amplifier circuitry, should be small enough to fit in a back-pack assembly. The operator would then be free to hold the transducer element in contact with the wall and observe the real-time display on a small screen incorporated in the hand-held unit. Also, due to the complexity of a multi-transducer system and the logistics of positioning more than one transducer by a single individual, it was determined that the brassboard prototype would feature a single transducer that would give range information but would be limited in two-dimensional spatial information to the extent of the transmit cone angle of the transducer (about 30°).

The hand-held assembly was designed to enable the user to see in real time the location and intensity of any detected return signals indicating the presence of an individual. A small, color video display panel is located above the transducer housing and connected to the Dell laptop (in the backpack) via a 5-foot cable assembly. The laptop is placed in "secondary" or "external monitor" mode prior to its being positioned in the backpack and then the hand-held display is activated. By not having the display on the laptop active, battery power is conserved.

The hand-held assembly consists of a trigger activator for the transducer pulsing circuit, a signal threshold control knob, a hi-lo power setting, and two power indicator lights: red for battery power and green for transmitter power (trigger activated). The low power setting is used primarily for laboratory calibration but could also be useful on walls that have a longer ring-down time for the initial applied pulse. The unit would normally be used in the high power setting. Positive-locking cable connections (one for the high voltage pulser and one for the low voltage power, video, and data signals) are located on the bottom of the housing. Figures 8 and 9 show photographs of the hand-held transducer assembly.

Figure 8. Photograph of the hand-held TWS sensor assembly showing the video display screen, threshold control knob, power switch and indicators.

Figure 9. Side-view of the TWS hand-held assembly showing the cable connections on the bottom for the high voltage pulse signal, video, and power feeds.

The transducer itself (Airmar AR-30) was designed to be acoustically isolated from the housing to minimize unwanted noise signals. It is also electromagnetically shielded to minimize electronic emission pick-up. The face of the transducer protrudes about 1/8 inch beyond the end of the housing to allow for direct contact to the wall. A gel cream is normally used to minimize air pockets at the transducer/wall interface, but for situations where this is not acceptable, a specially formulated polymer pad is available for making contact with the wall. The polymer pad reduces the sensitivity of the detector by about 6 dB (factor of 4). The transducer is shown in Figure 10 prior to the assembly of the plastic housing to illustrate its location and the acoustic dampener.

The high-gain receiver amplifier is located in the housing assembly to reduce the length of the received signal cable and, thereby, further reduces any unwanted noise on the received signal line. Low voltage power is delivered to the hand-held housing from the backpack. This DC power is used to drive the small panel video display as well as the high-gain receiver amplifier. The high voltage pulser cable is routed as a separate shielded coaxial cable from the backpack (where the pulser circuitry is located), again to minimize noise levels due to cable coupling. The amplified received signal is then routed back to the A/D unit located in the backpack where it is sampled and then processed by the software resident on the laptop computer. The laptop then sends the processed data and graphical real-time display back to the hand-held video display screen for viewing.

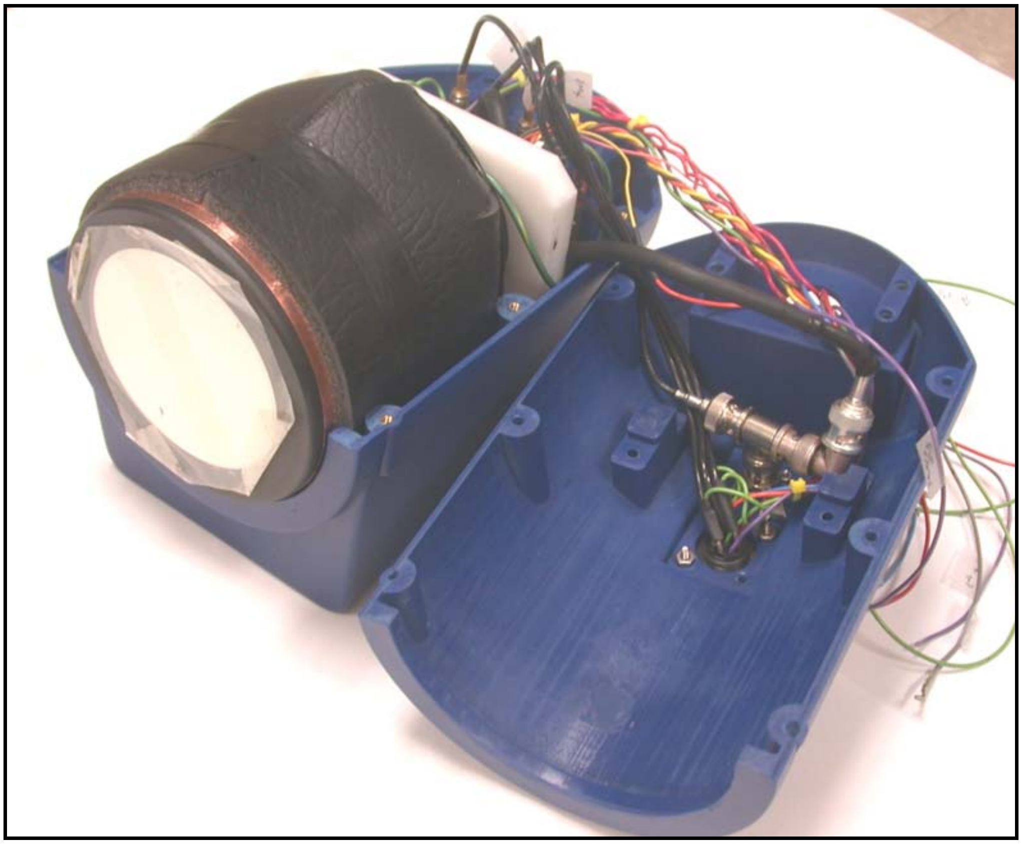

Figure 10. Photograph of the AT-30 transducer showing its location in the sensor housing.

Aside from the high-gain receiver amplifier, the two main components of the breadboard electronics; i.e., the low voltage ultrasound frequency generator and the high voltage pulse generator, were designed to be located on a single circuit board assembly. This board is then powered by rechargeable batteries and enclosed in a shielded box that is located in the backpack. Figure 11 shows a photograph of this box with the lid removed to allow for viewing of the various components located within.

The backpack is a commercially available unit that was modified to allow for rigid positioning of each electronic box inside the backpack. Velcro straps and tie-downs were sewn into the backpack to achieve this. Figure 12 shows photographs of the backpack with the rear zipper open to show the various components inside and with the zipper closed (normal operation). Shielded coaxial cables are used to interconnect each box inside the backpack as needed. Figure 13 shows a block diagram of the entire brassboard design.

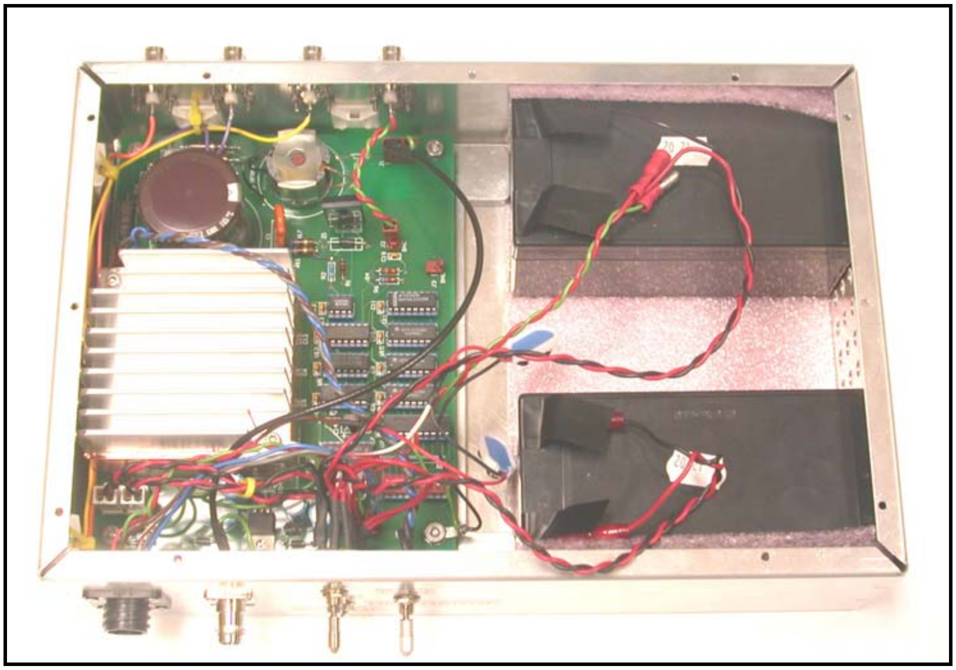

Figure 11. **Photograph of the low voltage power supply and high voltage pulser circuitry. This box is located in the back-pack assembly during normal operation.**

Figure 12. **Photographs of the backpack assembly showing (left-hand photo) the separately bagged components and (right-hand photo) the backpack zipped close for use.**

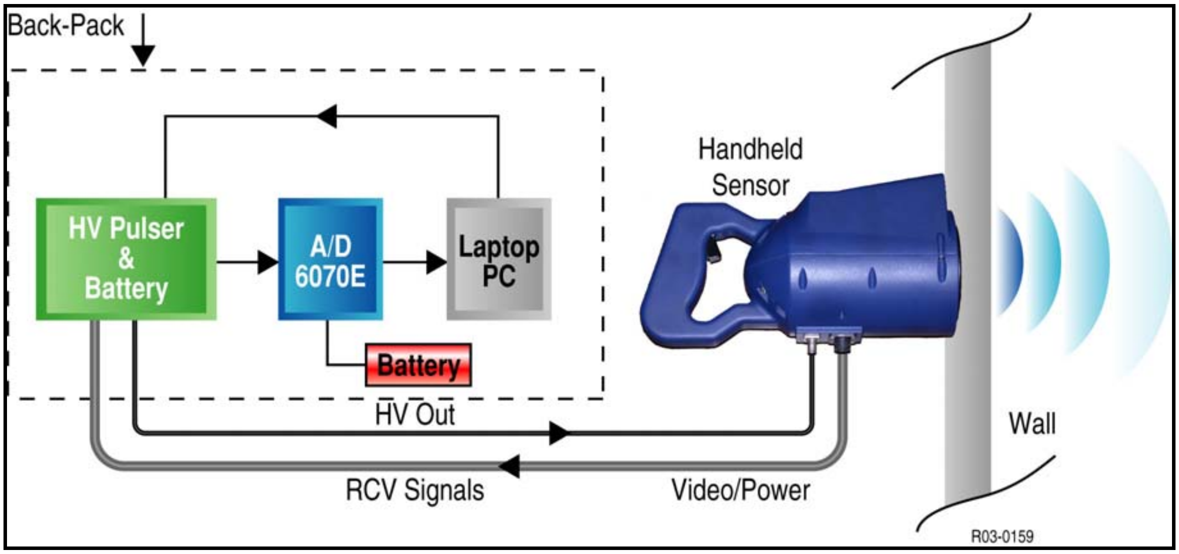

Figure 13. Block diagram of the brassboard TWS system showing the main components inside the backpack (HV pulser and battery, A/D unit and laptop) and the sensor connected by cabling to the backpack.

2.3 Fabrication and Assembly of The Prototype Brassboard TWS System

The fabrication and assembly of the brassboard prototype TWS system proceeded along several parallel paths. After determining all of the desired display features and controls on the hand-held unit, the transducer housing was drawn up and sent out for fabrication to a local plastic mold vendor. These parts were fabricated using a relatively low-cost stereo-lithographic apparatus (SLA) technique that allows for the production of 15 to 20 molded parts per SLA master part. Four separate parts that screw together were made for the housing assembly (two for the handle and two for the main body), as shown in Figures 14 and 15.

While the plastic parts were being fabricated, the electronic circuit that controls the ultrasound frequency generation and high voltage pulse generation was drawn up schematically and then sent out to a local printed circuit board manufacturer for fabrication. The boards were then populated with components by hand at Jaycor. After assembly, the board was tested to ensure that the design specifications were achieved. A photograph of the finished circuit board assembly is shown in Figure 16.

Figure 14. Photograph of the two plastic sensor housing pieces that contain the transducer and low noise, high-gain amplifier, as well as the video display panel, lights, threshold controller, hi/lo power switch, and cable connectors.

Figure 15. Photograph of the two plastic pieces that form the handle for the TWS sensor and contain the trigger activated switch assembly.

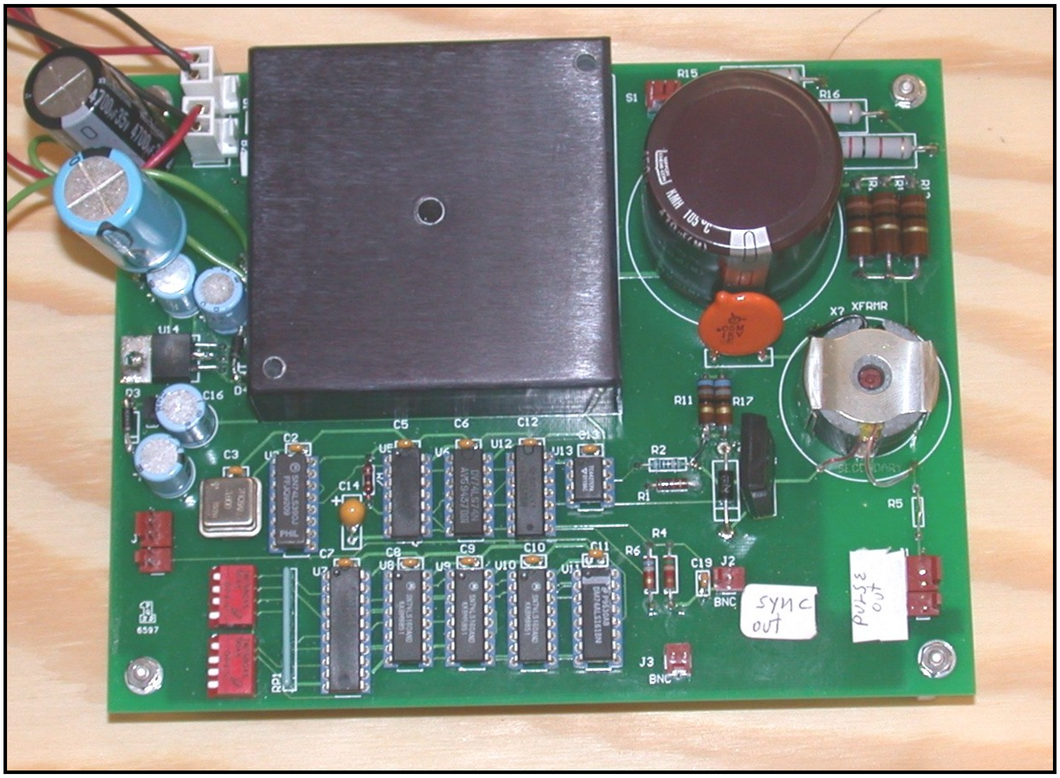

Figure 16. Photograph of the main high voltage pulser circuit board and 30-kHz waveform generation circuitry. This board is housed inside the backpack.

In parallel with the above efforts, the back-pack assembly was being fabricated by Jaycor machinists working together with a local fabric sewing vendor. Each element in the backpack was arranged to fit within the backpack and be compatible with the necessary interconnecting cables. Since the laptop computer and the high voltage pulse circuitry both require air flow to prevent overheating, the backpack was modified to allow for adequate air flow through and around these elements. A battery operated internal fan was also installed in the high voltage pulse unit to ensure good air flow across the DC-to-DC high voltage converter. Figure 17 shows the side panels on the backpack that allow for air flow through the backpack. As shown in Figure 18, a separate padded carrying case was also fabricated to protect the transducer housing assembly during transport and storage when not in use.

After receiving the finished plastic parts and assembling and testing the circuit boards, assembly of the hand-held transducer housing and back-pack electronic components took place during the final three months of the effort.

Figure 17. **Photograph of the lower side of the backpack showing the vents for airflow in the high voltage pulser box. The side of the backpack is also ventilated and covers the box when in use.**

Figure 18. **Photograph of the carrying case that was fabricated for use with the hand-held sensor assembly. The two cables are stowed in a compartment inside the backpack.**

3.0 RESULTS AND DISCUSSION

This section of the Final Report will present the results of the various improvements to the breadboard sensor design that resulted in the fabrication of the demonstration brassboard prototype. A discussion of these results and an assessment of the performance of the resultant brassboard design in terms of the range and probability of detection are also presented.

3.1 Wall Material Characterization Measurements

As discussed in Section 1, the optimum frequency for a TWS ultrasonic respiration monitor is about 25 to 40 kHz. Frequencies above 40 kHz tend to be severely attenuated in both air and in the various wall material types being considered. We have compared the TWS sensor performance at two different frequencies (30 kHz and 41 kHz) as a function of various wall material types and thicknesses. Figure 19 shows representative one-way (single-pass) attenuation data for various wall material types. For most materials tested, there was no significant difference between the 30-kHz and 41-kHz attenuation factors.

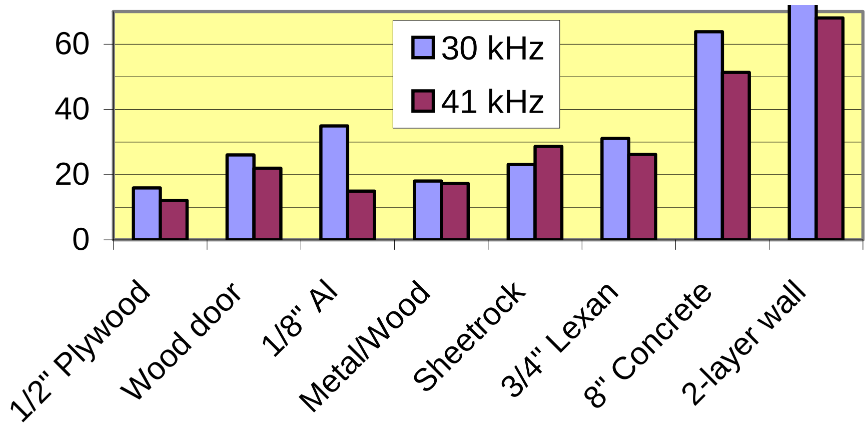

Figure 19. Measured single-pass attenuation (dB) of ultrasound through various wall material types at 30 and 41 kHz.

Much of this data was obtained on Jaycor's TWS laboratory testbed shown in Figure 20. In this testbed, one of the walls was configured with a removable panel to allow for different wall materials to be inserted and characterized. Other materials were characterized in actual wall settings on buildings and vehicles located near Jaycor's San Diego, CA facility.

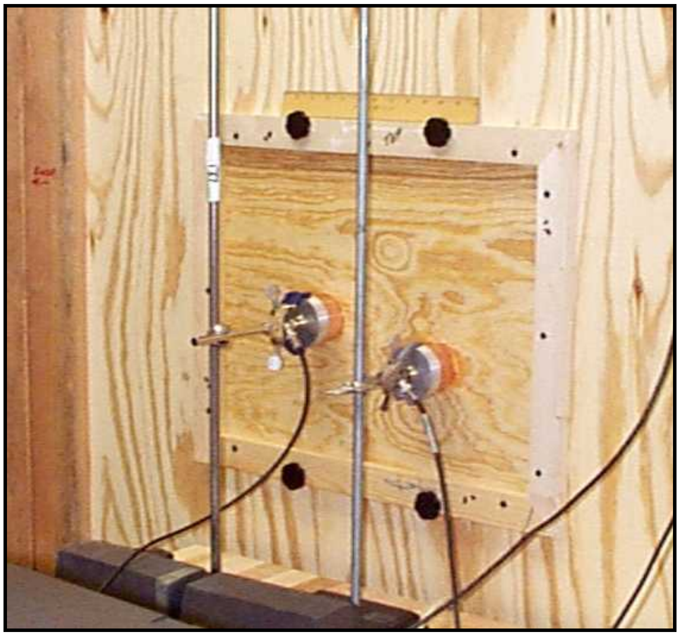

Figure 20. Photograph of one of the laboratory testbeds for characterizing different wall material types. Shown are two 41-kHz transducers mounted on a wooden panel with wallboard attached to the other side.

With the present high-gain receiver amplifier being used in the prototype brassboard system, the limit of detection; i.e., the maximum amount of attenuation that can be tolerated, is about 50 dB for a single-pass wall attenuation value at 30-feet range, and 60 dB at 10-feet range. Thus, the 8-inch concrete wall, with over 60 dB one-way attenuation, and the double layer wall (2 layers of drywall with a 3-inch air gap) with 70 dB one-way attenuation are beyond the limits of detection even at a reduced range of 10 feet.

Additional wall materials that were examined include red brick (4”-thick), cement (2”-thick), concrete (6”-thick, solid and with air gap), and glass (1/8”-thick). The attenuation through the glass was very similar to the 3/4-inch polycarbonate (Lexan) material that was tested (about 30 dB). The other materials performed similarly to the 8”-thick concrete material, but scaled in rough accordance with the thickness of each type.

It was noted in several instances that, for multi-layer walls and for hollow-block concrete walls, the structural cross members that provide support for the two inner and outer faces also provide a path for ultrasound energy to traverse the inner air gap. For example, in a two-layer wall with

2 x 4 vertical and cross stud members, if the transducer was placed directly over one of these cross-members, the wall behaved more like a single-layer wall than a two-layer wall. Single-pass attenuation values of 40 to 55 dB were observed in this manner on two-layer walls that normally had an attenuation of 70 to 75 dB.

Some limited testing was also performed at 60 kHz; however, the attenuation factor was observed to increase by a factor of 6 to 10 for wood and concrete materials relative to the 40 kHz data. While the AR-41 transducers are smaller, physically, relative to the AR-30 transducers, there is an advantage to using the 30-kHz source rather than the 41-kHz source since it can be driven at higher pulse power levels and, thus, deliver more energy than the 41 kHz source. The slightly higher absorption in moist air at 41 kHz (1.4 dB/m versus 1.0 dB/m at 30 kHz) can also adversely affect system performance at longer ranges and high relative humidity.

Another consideration is that an individual’s thoracic displacement during respiration is a larger fraction of an 8.4-mm wavelength (41 kHz) than of an 11.4-mm wavelength (30 kHz). Thus, the phase change produced by respiration is more pronounced at the higher frequency and, thus, the detector is inherently more sensitive at 41 kHz than at 30 kHz for a given incident power intensity. However, since we can get more incident power on target using the 30-kHz transducers, it was determined that the brassboard sensor would incorporate a 30-kHz transducer. Should weight considerations become critical, a lighter weight AR-41 transducer could be substituted for the AR-30 transducer with some degradation in performance; i.e., reduced range.

With regards to lower frequency operation, using frequencies below 25 kHz poses the risk of being heard (for covert applications), as the human auditory range is generally considered to extend up to 20 kHz. However, since the 10- to 20-Hz pulse-train “clicks” generated by the present system will most likely be audible anyway, a better reason for avoiding lower frequencies is that the transducers get even bigger, heavier, and more expensive than the AR-30 transducers at lower frequencies.

As discussed previously, the main sources of energy loss for TWS are in the air-wall transmission interface and in simple $1/r^2$ divergence effects. Thus, it is important to minimize the number of interfaces through which the ultrasound must pass. For this reason, it is necessary to closely couple the ultrasound source to the outer wall of whatever enclosure is being surveilled. It is for this reason that the ultrasonic TWS monitor has no inherent standoff capability. Also, due to the high losses at air-wall interfaces, the monitor cannot see through a second interior wall.

For most of the test measurements, close coupling of the transducers to the wall was achieved by applying a gelatinous cream to the flat front surface of the transducers and then pressing the faces of the transducers against the outer wall. The cream produces a very close coupling by filling in small air pockets and voids in the wall surface, boosting the return signal by orders of magnitude. Our measurements indicate that virtually none of the wall losses occur at the interface of the outer wall with the cream-covered transducer face, and that virtually all losses occur at the inner wall/air interface.

As an alternative to the gel for close coupling, a number of different polymer rubber materials were examined. These materials showed promise of providing good transducer coupling without seriously degrading the net transmitted ultrasonic power. In order to quantify the performance of the various materials being examined, a double-pass configuration was set up in the laboratory using a metal clad (1/16-inch aluminum) piece of wood (1/2”-thick) as a representative wall material. For each material tested, the power needed to drive the transducer for an equivalent received signal amplitude was noted. The target was a stationary reflector positioned at a distance of 6 feet behind the “wall.” Table 1 shows some of the results versus the durometer of the material. The durometer is a measure of the relative hardness of the rubber; the higher the durometer, the less compressible the material.

Table 1. Measured relative drive voltages needed for the equivalent return signal response compared to a thin layer of Vaseline for 1/16-inch polymer rubber with varying durometer.

	DUROMETER					
	Vaseline	20	30	40	50	70
Equivalent Drive Voltage	1	9.71	6.38	3.00	4.44	6.26

There appeared to be a minimum in the drive voltage needed to get the equivalent response (relative to just a Vaseline layer) at a durometer of 40. While the voltage difference is a factor of 3 relative to the gel/Vaseline only case, note that this translates into a factor of 9 in power. Circular pads of this material (Sorbothane part number 0208065) were fabricated for use with the TWS sensor. The pads have a self-adhesive backing that facilitates application of the material directly to the face of the transducer and also acts to improve the coupling at that interface.

To facilitate eventual remote, autonomous operation of the sensor, a stand-alone mounting fixture was designed and fabricated. The fixture consists of a stainless steel gimbal mount that holds a single transducer element against a wall. The gimbal mount is supported on two legs that can pivot with respect to the gimbal mount. The weight of the mount (about 26 lbs., with transducer) is enough to provide good contact between the transducer face and the wall surface. This fixture was used in a number of the laboratory characterization tests since it provided a very reproducible force at the transducer/wall interface. A photograph of the transducer mount is shown in Figure 21.

Figure 21. Photograph of the stand-alone mounting fixture designed to apply a uniform force on the transducer/wall interface.

3.2 High Voltage Pulser Performance

The breadboard pulser was originally designed to provide a 1,500 V, peak-to-peak, driver for the Airmar transducer element. Since the AR-30 can tolerate up to 2,200 V, peak-to-peak, a new high voltage pulser circuit was designed, built, and implemented as part of the brassboard prototype sensor. The basic circuit consists of a low voltage ultrasound frequency generator followed by a high voltage, step-up transformer circuit. The low voltage circuit initially generates a 5-V, peak-to-peak, 30-kHz square wave. This is then time-gated to provide for the desired number of cycles, typically 12 to 13 per burst, and is repetitively pulsed at the desired rate, typically 9 to 10 Hz. This low voltage waveform is then used to drive a high voltage, high current MOSFET transistor that is connected to the primary of a high voltage, step-up transformer. For the brassboard prototype, these transformers were custom wound and obtained from a vendor who works with Airmar to supply his transformer needs.

A switch on the brassboard hand-held assembly allows the user to select between a low power and high power setting. In the high power setting, the high voltage pulser is capable of providing a 2,100 V, peak-to-peak, 13 cycle waveform to the transducer element. In the low power mode, this is reduced to about 1,200 V, peak-to-peak. The low power mode is used for wall types that are less attenuating, such as on vehicles, where the higher return signal might saturate the high-gain receive amplifier. We also use the low power setting for calibration measurements in the laboratory.

Table 2 lists the measured pulser output characteristics for both the breadboard and brassboard designs. Note that the piezoelectric transducers work most efficiently when driven with square wave inputs rather than with sinusoidal inputs.

Table 2. Measured pulser characteristics for the breadboard and brassboard designs.

	BREADBOARD	BRASSBOARD
Amplitude	1,500 V peak-to-peak	2,100 V peak-to-peak
Output power	3-kW peak	5 kW peak
Pulse width	16 µs per pulse (33 µs period)	16 µs per pulse (33 µs period)
# of Pulses	8-12	10-13
Rep-rate	7-9 Hz	9-10 Hz
Duty cycle	0.2-0.3%	0.3%

3.3 Comparison of Breadboard and Brassboard Prototypes

One of the main goals in transitioning from the breadboard demonstration system to the brassboard prototype was to reduce the size and weight of the sensor system to allow for hand-held operation. The largest and heaviest component of the breadboard system that was targeted for size reduction was the desktop computer (with internal A/D board and external interface) and its display monitor. Weighing over 85 lbs., the desktop computer and display monitor were replaced with a laptop computer (8 lbs.) and small panel video display mounted in the hand-held assembly. As discussed in Section 2.1, the total weight of all the components in the breadboard system was 120 lbs. For the brassboard system, the hand-held assembly, with transducer, weighs 5.5 lbs. The backpack components weigh about 38 lbs., with almost half that weight (16 lbs.) consisting of the batteries for the laptop, A/D unit, and pulser circuitry.

In terms of range and sensitivity, the breadboard system was capable of detecting a single person standing motionless and breathing normally at distances out to 18 feet (6 meters) behind a solid wood door. With the increased drive voltage and current capability in the brassboard pulser electronics, as well as the increased sensitivity of the low-noise amplifier, we are now able to detect a motionless individual (breathing normally) behind a solid wood door out to a distance of 30 feet (10 meters) using the stand-alone mounting gimbal for the transducer.

For the final brassboard configuration, with all of the components mounted in the backpack and hand-held assembly, this detection range was significantly reduced to about 10 feet (3 meters) as a result of self-generated EMI coupling into the high-gain amplifier. One of the main sources of this EMI appears to be the color plasma display unit in the hand-held assembly. The transducer is shielded to some extent against EMI pick-up, but the front end is necessarily open and much of the noise level is generated by coupling into the transducer receive circuitry through this aperture. Also, the signal cable for the display panel runs inside the same cable bundle that carries the received signal and DC power cables. The video switching noise generated inside this bundle appears to be coupled to the power and the received signal to the extent that, together with the coupled EMI on the transducer receive circuitry, the baseline noise floor was seen to increase from a normal level of about 200 to 250 mV up to levels as high as 1 V (1,000 mV). This very high level of random noise makes detection of truly time-varying signals very difficult.

In order to improve the performance of the brassboard prototype design, this noise source must be eliminated. Potential solutions include routing the video cables in a separate cable bundle and also converting from a color plasma display to a back-lit LCD display type to minimize EMI generation.

The EMI shield on the transducer itself should also be examined to determine if any improvements or increase in shielding are possible. This shield was developed by Jaycor to minimize the amount of EMI pick-up on the transducer when in the receive mode. A grounded circumferential shield was designed and proposed to Airmar by Jaycor and they proceeded to implement the design on the new AT-30 transducers. However, the shield does not cover the front end of the transducer and this aperture is now the dominant entry point for EMI pick-up. It is possible that a thin coating of a conductive material such as aluminum or nickel-silver alloy over the front face would provide a complete shield while have a minimal impact on the ultrasonic conductance properties of the transducer.

4.0 CONCLUSIONS

The main objectives of the TWS development effort were to demonstrate a breadboard system for proof-of-principle, and then design and fabricate a brassboard prototype system for portable use. The breadboard demonstration system was successfully completed ahead of schedule prior to the end of the first year of the effort. Several demonstrations of the sensor were made where a person seated or lying down was detected through a solid door simultaneously while a second person was standing or pacing at some distance behind the first subject. Additional tests were carried out on enclosed panel trucks with the engine running that showed that individuals could be detected inside. Many of the features implemented on the breadboard system were then modified and incorporated into the design and eventual fabrication of a man-portable brassboard prototype system. The portable system consists of a back-pack assembly that contains the acoustic pulse forming circuitry, data processor, and battery power. The attached hand-held unit consists of a single high power transceiver with a two-dimensional display panel and associated power and threshold setting controls. Due to unexpectedly high electrical noise on the hand-held receive amplifier, the sensitivity of the brassboard system is lower than the breadboard system in terms of effective range (about 15 feet versus 30 feet). This noise appears to be generated by the display panel and, to a lesser degree, the laptop and A/D processor in the back-pack assembly.

A number of presentations were made during the course of this effort at various Program Review meetings and public forums such as the SPIE Conference held annually with regards to LE technology. Two papers were generated during the course of this effort and published by the SPIE as part of their conference proceedings [Ref. 6, 8].

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