Large Vibrometer Arrays for Seismic Landmine Detection

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ABSTRACT

Inexpensive ground-contacting accelerometers have been demonstrated in field experiments as appropriate vibrometers for a seismic landmine detection system. A thirty-two-element line array of these has been used to detect a variety of anti-tank (AT) landmines under realistic field conditions. Images of data measured by scanning this line array to synthesize a larger plane array have shown that the two-dimensional array offers potential advantages in terms of both measurement speed and landmine image contrast. The simultaneity of measurements with a physical array, as compared to synthetic array measurements that have been performed in the past, presents opportunities for improved landmine detection algorithms. Issues pertaining to the implementation of large arrays of vibrometers include sensor fidelity, array fidelity, scalability, and safety. Experimental measurements with prototype sensors in the laboratory and at a field test site have demonstrated the robust and repeatable ground coupling of the sensor in sand, dirt, gravel, and grass. Ground loading has been investigated with multiple array configurations with the dominant effect being an increase in the wave speeds of the surface waves. While the field experiments with the line array were conducted using commercially available data acquisition hardware and software, a custom data acquisition and processing system has been developed to meet the requirements of a large array of sensors. A lightweight sensor ensures the safety of touching the ground over buried landmines as the contact force is significantly less than the force required to detonate typical anti-personnel (AP) landmines and AT landmines.

Keywords: Seismic, Landmine Detection, Ground-Contacting, Vibrometer, Array

1. INTRODUCTION

In recent years, seismic landmine detection techniques have been investigated with near-ground and ground-contacting sensors [1-4] as an alternative to non-contact sensors such as radar[5] and laser-doppler vibrometers[6-8]. Ground-contacting seismic sensors can effectively eliminate the primary problem associated with seismic landmine detection techniques, the required measurement time. The measurement time needed to scan a given region can be reduced by increasing the number of sensors. Large arrays of sensors are possible due to the relatively inexpensive cost per sensor of

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approximately $50 using off-the-shelf components. For example, a 32 by 32 element array could measure the surface motion in a 1m^2 region in less than one second. Ground-contacting accelerometers are also more sensitive than non-contacting sensors, especially at high frequencies. Although ground-contacting sensors would not be suitable for a fast-progressing platform, a large array of ground-contacting sensors would be ideal as a confirmation sensor due to their short measurement time and accuracy. Smaller arrays could be used on multiple robotic platforms in a coordinated search mode.

While ground-contacting sensors present several advantages for seismic landmine detection systems, the following issues must be addressed for successful design and implementation in large arrays: sensor fidelity, array fidelity, scalability, and safety. The range of field environments that could be encountered during landmine detection operations mandates that the coupling of the sensor to the ground be repeatable and robust. Just as each sensor must be non-intrusive, a large array of sensors must not adversely affect the measurement through scattering between elements in a periodic array or through ground loading. Additionally, the implementation of a large number of sensors necessitates data acquisition hardware and software capable of simultaneously acquiring a large amount of data, storing and/or transferring it to a computer, and then processing it with imaging and detection algorithms. Safety can be ensured by proper design of a lightweight sensor. Typically, anti-personnel (AP) landmines require forces of 20 to 150 N for detonation while anti-tank (AT) landmines require forces that are an order of magnitude larger[9]. If the sensor is designed to exert significantly less force than these values, contacting the ground above a buried landmine with the sensor should not pose a safety problem. These issues have been addressed in the following sections through experiments to demonstrate the fidelity of the sensor and array configurations and the redesign of the ground-contacting accelerometers with a new data acquisition technique that is scalable to a large number of sensors.

2. SENSOR DESIGN AND COUPLING

After building and testing several prototype sensors, a sensor design, shown in Figure 1, was selected for field testing at a U. S. Government test facility in a temperate climate. The sensor design, development, and testing have been described in detail in the literature[1,2,3]. Experimental measurements with the prototype sensors have demonstrated repeatable and robust coupling to the ground in sand in the experimental model and in dirt, gravel, and grass at the field test site. The sensor was 46 cm long and 1.9 cm diameter with a minimum mass of 156 g with one steel shaft collar. Additional shaft collars were used to vary the tail mass of the sensor during testing. A total of 50 sensors were assembled for testing. Data from field testing with a 32-element linear array of sensors with a VS-2.2 AT landmine are presented as an image on a 30 dB scale in Figure 2a for a scan of a 1 m^2 region. Similarly, data from a scan of a single sensor over a VS-1.6 AT landmine buried 8 cm deep in the experimental model[5] at Georgia Tech are presented as an image in Figure 2b. Each image has been scaled to its own maximum value. A 10 by 3 array of sensors has also been tested in the experimental model over a 3 m^2 region.

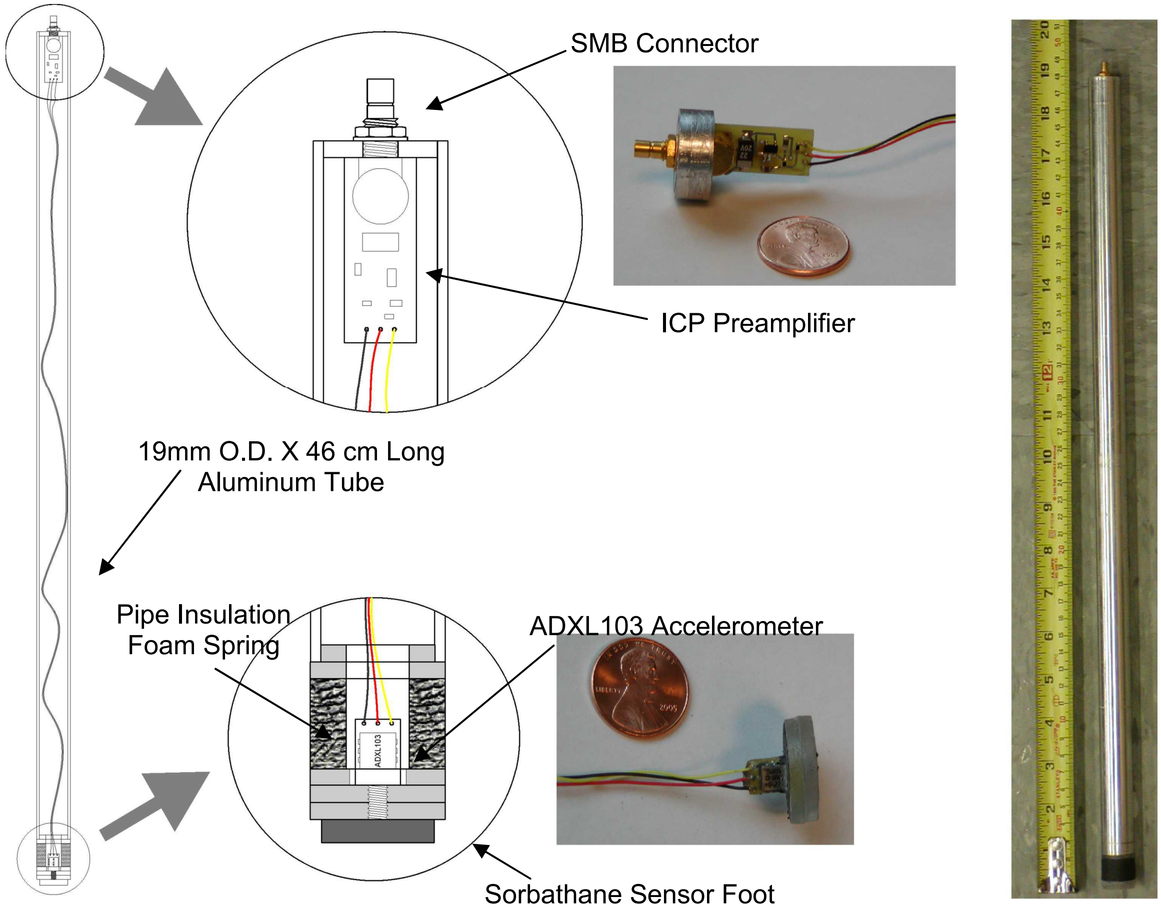

Figure 1: Ground-Contacting Accelerometer Sensor Photographs and Drawings.

3. ARRAY FIDELITY

Just as each sensor must be non-intrusive, a large array of ground-contacting sensors must not adversely affect the propagation of surface waves through the measurement region. It is not inconceivable that the periodic loading of the soil surface could be problematic due to mutual scattering amongst the sensors in a large array. However, previous measurements with the 10 by 3 sensor array in the experimental model and the 32 sensor linear array at the field site did not indicate any problems. To investigate the effects of ground loading of larger arrays upon the propagation of Rayleigh surface waves, two experiments were conducted in the experimental model utilizing mock sensors in different array configurations. Wooden dowels with steel shaft collars represented the tail mass of the sensors while the same foam spring used in the actual sensors was the spring in the mock sensors. An array holder, shown in the two configurations in Figure 3, was constructed to position the mock sensors in the scan region.

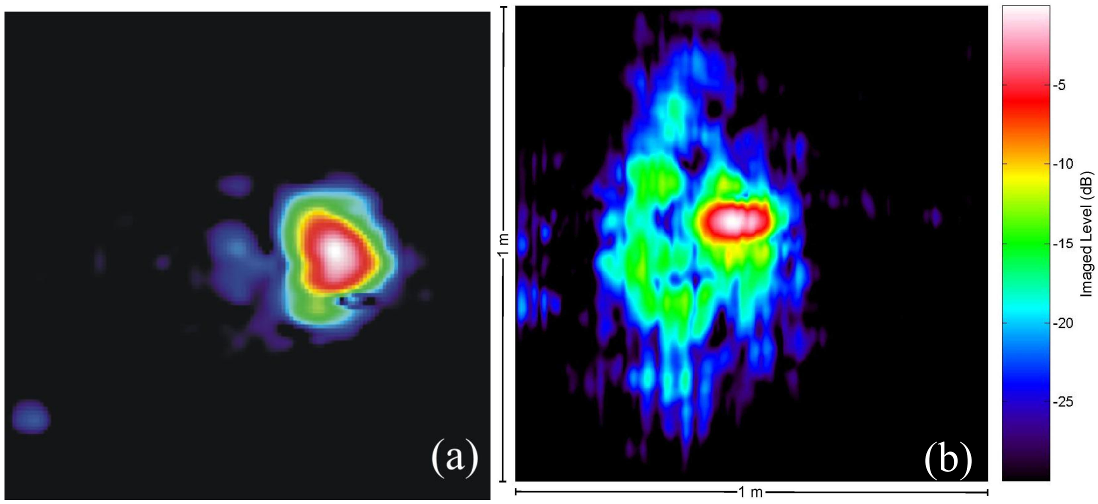

Figure 2: Images from Field and Laboratory Experiments with Ground-Contacting Accelerometer Sensors with (a) 32-Element Linear Array over a 1 m^2 region with a VS-2.2 AT Landmine at a U. S. Government Test Facility and with (b) a Single Sensor Scanned over a 1 m^2 region with a VS-1.6 AT Landmine Buried 8 cm Deep in the Experimental Model at Georgia Tech.

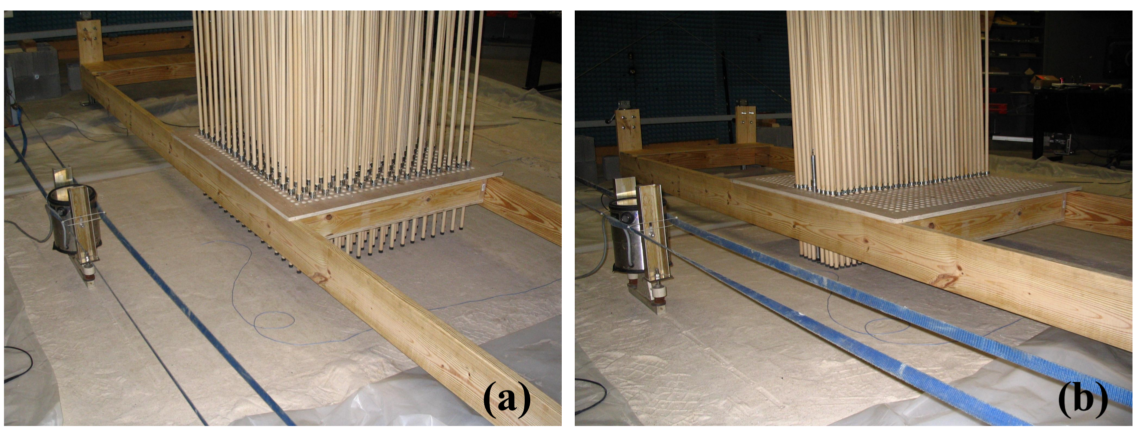

Figure 3: Laboratory Experiments on Ground Loading by Large Arrays of Sensors with (a) 16 by 16 Array of Mock Sensors Covering 1m^2 and (b) 9 by 32 Array with One Line of Ground-Contacting Sensors.

In the first experiment, a 1 m^2 region was populated with a 16 by 16 array of mock sensors. The first line of the array was positioned 81 cm from the seismic source shown in Figure 3. Triaxial accelerometers were buried just beneath the surface to measure surface accelerations 30 cm in front of the first line of the array and 29 cm beyond the last line of the array. First, surface waves were generated by the seismic source and measured by the two triaxial accelerometers without the effect of the array loading the ground. Then, the ground was loaded by the array of mock sensors and the measurement was repeated. The data are presented for the unloaded (shown in red) and the loaded (shown in black) conditions in Figure 4(a) for the accelerometer located in front of the array and in Figure 4(b) for the accelerometer located beyond the array. In Figure 4(a), it is apparent that the ground loading of the array had no significant effects upon the measured surface accelerations in front of the array. The incident waveform appears identical in both the loaded and unloaded cases which indicates that there is not a significant reflection of the surface waves from the array. In Figure 4(b), the pulse arrives earlier in the loaded case with approximately the same shape. Thus, the dominant effect observed by the ground loading of the array is a slight increase in the propagation speed of the surface waves. This result was not unexpected as the anticipated effect was static compression of the near-surface layers (effectively increasing the overburden pressure) of the soil, which will increase the propagation speeds of the surface waves.

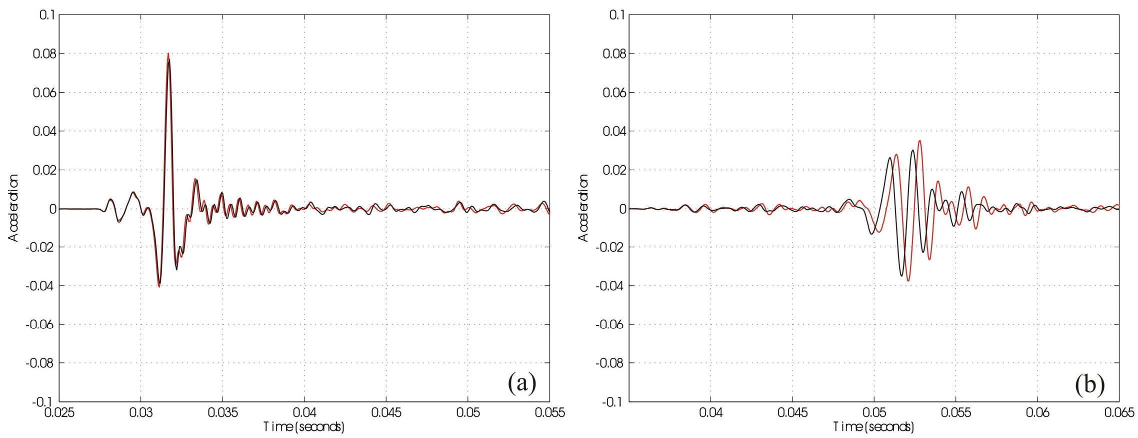

Figure 4: Normal Surface Acceleration With and Without Ground Loading of 16 by 16 Array of Mock Sensors Covering $1m^2$ (a) in Front of and (b) Behind Array Location (Red lines indicate data without ground loading while black lines indicate data with ground loading).

The mock array was reconfigured for the second experiment as a 9 by 32 element array with one line of 32 ground-contacting accelerometers from the field tests along the centerline of the array. For the first measurement, the ground-contacting accelerometers were placed on the soil and the normal surface accelerations were measured for the unloaded case. For the second measurement, the eight lines of mock sensors were lowered into contact with the soil (in addition to the line of ground-contacting accelerometers from the first measurement) and the normal surface accelerations were again measured as the loaded case. The data from these two measurements were then used with wave extraction techniques[10, 11] to determine the phase velocity of the Rayleigh surface wave for the two conditions, as shown in Figure 5. The predominant effect observed in Figure 5 is of increased phase velocity due to the ground loading of the array. The effect increases with frequency as would be expected. The dominant surface wave, the Rayleigh wave, decays in amplitude with increasing depth in the ground. Therefore, the higher frequency components, which

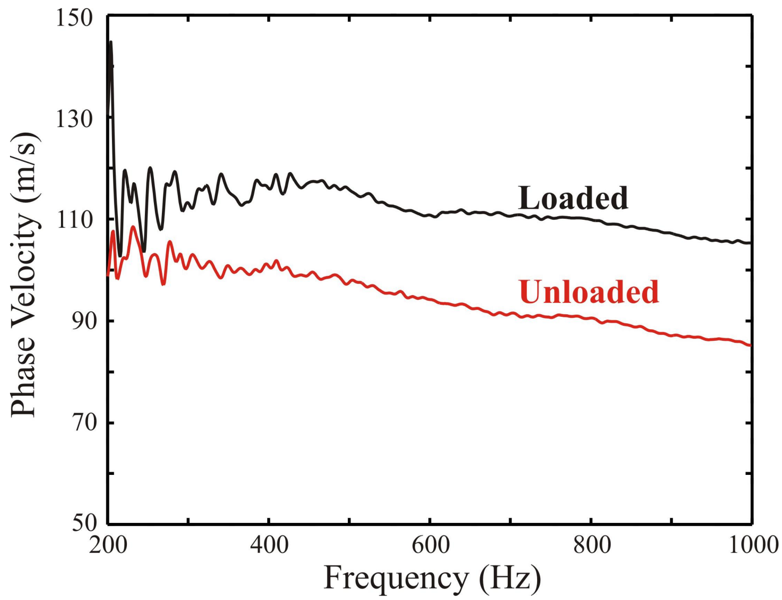

Figure 5: Phase Velocity of Rayleigh Surface Wave With and Without Ground Loading of 9 by 32 Array with One Line of Ground-Contacting Accelerometers Along the Centerline of the Array.

will have shorter wavelengths, only penetrate the near-surface layers. Because the surface loading compresses the near-surface layers, the phase velocity of the higher frequency components (and corresponding smaller wavelengths) will be increased more than the lower frequency components.

4. SCALABILITY

Although the use of commercially-available data acquisition hardware and software provided the greatest flexibility for investigation and testing of the 32-element array in the field experiment[1-3], the same hardware and techniques are not practical for a large array of sensors. Therefore, a new data acquisition system has been designed and built based upon the field data and sensors.

The full 32 by 32 seismic sensor array contains 1024 low-cost accelerometers. While the sample rate of a single sensor is a relatively modest 4-8 kHz, continuously sampling a thousand sensors at this rate for several seconds without dropping any samples poses a challenge for most current data acquisition systems. Current commercial off the shelf (COTS) data acquisition solutions would be very large and cost prohibitive, since they do not scale well for such a large number of channels and sensors.

The new data acquisition system adds an analog to digital conversion chip to each ground-contacting sensor module. These modules are daisy-chained in groups of 32 to lessen the cabling issues. The system uses a system on-a-programmable chip (SoPC) technology to acquire the data from the large array of modules. In an SoPC system, a large new generation Field Programmable

Gate Array (FPGA) is used that contains both internal microprocessor core(s) and memory in addition to the traditional FPGA programmable logic hardware. The end user can add custom designed digital hardware for his application using the FPGA's logic elements and also run application software on the processor(s) inside the FPGA. This approach can offer many of the features and advantages of a custom ASIC chip design without the long development times and huge costs. A system level SoPC CAD tool environment provided by the FPGA vendor includes both hardware and software development tools for the FPGA. Hardware is designed using VHDL or Verilog, and application software is typically developed in C in current SoPC systems. The ability to add extensive custom hardware to interface thousands of sensors to a processor was ideally suited for this application.

The SoPC system used in the initial implementation of this system contains a Xilinx Virtex II Pro FPGA which contains two PowerPC processor cores, memory, and programmable logic elements. In addition to the FPGA chip, the small SoPC system board contains a 256MB-2GB memory module, Flash memory, an Ethernet network interface, and a PC style audio interface. Flash memory can be used to automatically load both the FPGA's hardware configuration data and software for the processor at power-on.

A block diagram of the SoPC based data acquisition system can be seen in Figure 6. Each row of sensors clocks its A/Ds digital sample data into the FPGA using a high-speed 1-bit serial data stream. Custom hardware in the FPGA for each row of sensors performs serial to parallel conversion using a shift register and FIFO memory buffers to store data samples. All rows can work in parallel, since each row has its own independent FPGA hardware interface and shift register. Since rows work in parallel, the system scales well for large numbers of sensors. The 256MB memory module can be used to buffer data samples. The PowerPC processor core inside the FPGA runs a web server application program that provides an easy-to-use web page style user interface to the system. The 100Mb/sec network interface is used to download data sample files to a PC for analysis.

The small interspacing of sensors required and the associated interconnect cabling also presents several challenges. A small double-sided surface mount printed circuit board was designed for each sensor. Each sensor board contains a low-cost 16-bit A/D with a serial peripheral interface (SPI) and an analog filter for the accelerometer's analog output. The serial A/D digital data outputs for each row can be daisy chained using a standard SPI 3-wire interface. The sensors are interconnected using low-cost mass-produced serial ATA cables and connectors that were developed for newer PC disk drives. One row of eight sensor boards is shown in Figure 7 along with the associated daisy chain cabling using the serial ATA cables.

At the time of this writing, the individual elements of the data acquisition system have been implemented and demonstrated. The FPGA web server application program downloads sample data files to the PC. A row of sensor boards has been successfully interfaced to the FPGA using a VHDL-based state machine and shift register. Data samples have been stored in the large memory buffer and read out by the processor. Work remains to integrate all of the hardware and software features into a single system with a large number of sensor boards.

In the future, it would also be possible to move some of the preprocessing of data samples from the PC to the FPGA. FPGAs can efficiently perform common DSP operations such as scaling, limiting, FFTs, and downsampling using high-speed hardware built from the FPGA's programmable logic elements and the FPGA's hardware multiplier circuits. Additional FPGA logic is available for this purpose and even larger and faster FPGAs are now available.

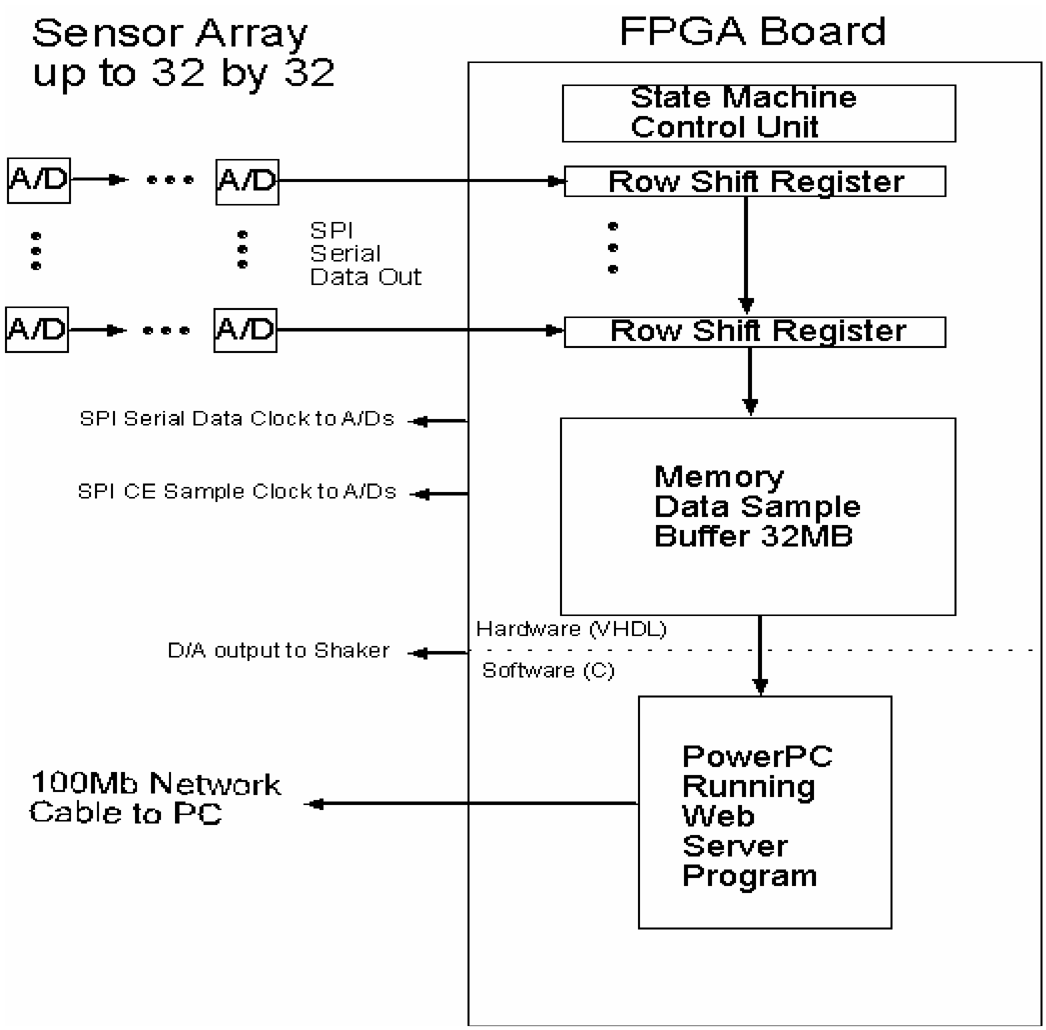

Figure 6: Block Diagram of Data Acquisition System.

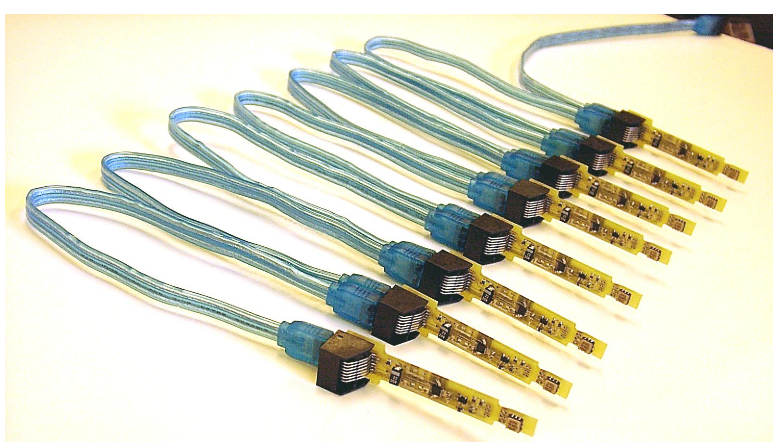

Figure 7: Row of Daisy Chained Sensor and 16-bit A/D PCBs.

5. CONCLUSIONS

The implementation of ground-contacting sensors in seismic landmine detection systems offers increased sensitivity with reduced measurement time through the use of large arrays of sensors. Concerns about sensor fidelity, array fidelity, scalability, and operator safety have been addressed through sensor design and testing, experiments in a laboratory model and at a U. S. Government test facility in a temperate climate, and development of a new data acquisition system suitable for a large array of sensors. Experimental measurements in sand, dirt, gravel, and grass have demonstrated that the sensor's coupling to the ground is robust and repeatable. Both AP and AT landmines have been detected in a variety of scenarios with different array configurations. Ground loading by a large array of sensors has not been a problem in the measurements. Experiments to investigate the effects of loading the ground with a large array of sensors indicate that the speed of the surface waves increases due to the presence of the array. Scattering amongst the elements in the array did not appear as a problem in the measurements; in fact, the measurements did not indicate that there was even a significant reflection from the array. To ensure that the data from a large array of sensors can be acquired in an efficient and timely manner, a new data acquisition system has been designed and tested. Laboratory testing of the data acquisition hardware with a small number of accelerometers indicates that the system functions as designed and is scalable to larger numbers of sensors. Safety should not be an issue as the contact force exerted by each of the sensors is significantly less than typical forces required for detonation of AP landmines and is substantially lower than the forces required to trigger AT landmines. Arrays of ground-contacting sensors could be utilized either as a confirmation sensor to scan a large region quickly or on robotic platforms in a coordinated search mode with multiple smaller arrays.

6. ACKNOWLEDGEMENTS

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