Advances in Acoustic Landmine Detection

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ABSTRACT

The phenomenon of the acoustic-to-seismic (A/S) coupling of airborne sound into the ground for buried anti-personnel and anti-tank landmine detection is well established [J. M. Sabatier and N. Xiang, IEEE Trans. on Geoscience & Remote Sensing, 39, pp 1146-1154 (2001); N. Xiang and J. M. Sabatier, J. Acoust. Soc. Am, 113, pp.1333-1341 (2003)]. A sound source is used to insonify the ground surface. The airborne sound couples into the soil and excites the vibrational energy of the soil matrix. An anomaly in the vibrational energy occurs on the ground surface in a region very near a buried landmine. This anomaly can be detected with a vibration sensor. This paper will discuss vibration sensors that are currently being used to measure the vibrations due to the presence of a buried landmine. These instruments include a geophone, laser, ultrasonic and radar Doppler vibrometers, and a whole field optical sensor. The detection ability of fused sensors comprised of the A/S laser Doppler vibrometer-based sensor and a ground penetrating synthetic aperture radar is also being investigated. Researchers at the University of Mississippi, Planning Systems Incorporated, and MetroLaser, Inc. are investigating all of the vibration sensors described above. This paper will present results of this research.

I. INTRODUCTION

When an acoustic wave strikes the ground surface, energy is coupled into seismic motion in the subsurface of the ground. This phenomenon is well-understood and is termed acoustic-to-seismic coupling (A/S) [1], [2]. When a landmine is buried lower than a few centimeters below the ground surface, it results in distinct changes in the A/S coupled motion. These changes can be sensed on the ground surface. Since the early 1980s, both theoretical and experimental studies of A/S coupling have been conducted by The University of Mississippi [3]. Different kinds of sensors, including geophones, laser, ultrasonic and radar Doppler vibrometers, and a whole field interferometer have been used to measure the ground vibration. Success in using a laser Doppler vibrometer (LDV) for A/S landmine detection stimulated development of a multiple laser beam LDV, and of fused sensors comprised of a LDV-based A/S detection sensor and synthetic aperture ground penetrating radar.

II. GEOPHONES

In the early 1980s, the A/S coupled surface vibration was measured using geophones, which are velocity sensors. The output voltage of a geophone is proportional to the vibration velocity on the surface to which the geophone is attached. For example, an L-10 geophone (manufactured by Mark Products Inc.) has high sensitivity over a frequency range between 50 Hz and 1 kHz. In an early study of A/S landmine detection, a geophone array of eight-by-eight geophones was deployed to measure the A/S coupling signals over a sub-patch of the ground. By displacing the array sub-patch by sub-patch, a larger patch could be covered.

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In this way, a map of data could be obtained showing the location of buried landmines [3]. Although geophones are contact sensors, they require only minimal electronics for functional operation. In humanitarian landmine detection, safe deployment of a low cost simple A/S coupling confirmation sensor using a single geophone with minimal electronics might still be conceivable. This single geophone technique will, of course, be very slow. The time to make a confirmation measurement for a target located within a 0.1 m^2 area could be on the order of a few minutes or less.

III. LASER DOPPLERVIBROMETRY

During the late 1980s and early 1990s an experimental study on the feasibility of using a laser Doppler vibrometer (LDV) was conducted by the National Center for Physical Acoustics at the University of Mississippi [4]. Through careful experimentation, it was possible to make the measurement results comparable between the LDV and geophone. More recently, measurements using a scanning LDV were performed [1], [2]. The scanning LDV used in the recent work was a single-laser, single-point device. The laser beam was controlled by two perpendicular mirrors in such a way that the beam could be deployed to any point within a predefined area of finite size. Fig. 1 schematically illustrates measurement setup. Fig. 2 shows the photograph of the laser-Doppler vibrometer-based acoustic-to-seismic landmine detection system used in the recent field measurements. Both stop-stare measurements and moving beam measurements have been studied with success [1],[2],[5].

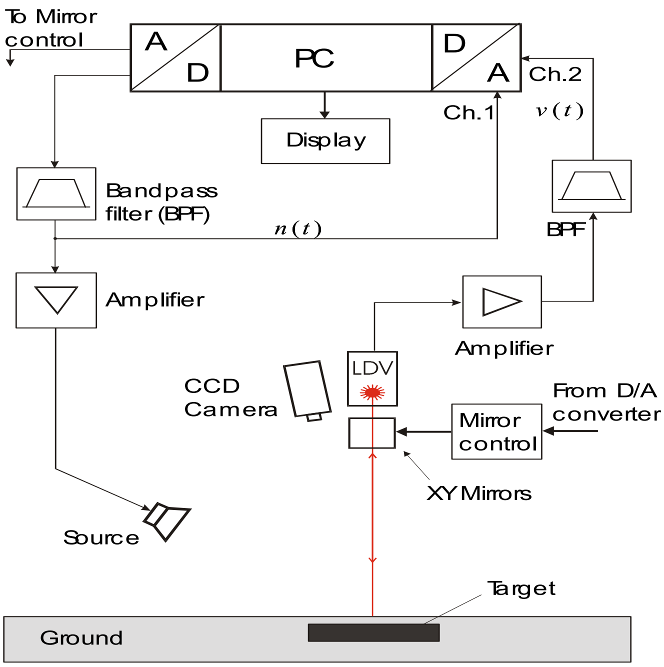


Figure 1. Schematic of the LDV-based acoustic-to-seismic landmine detection system.

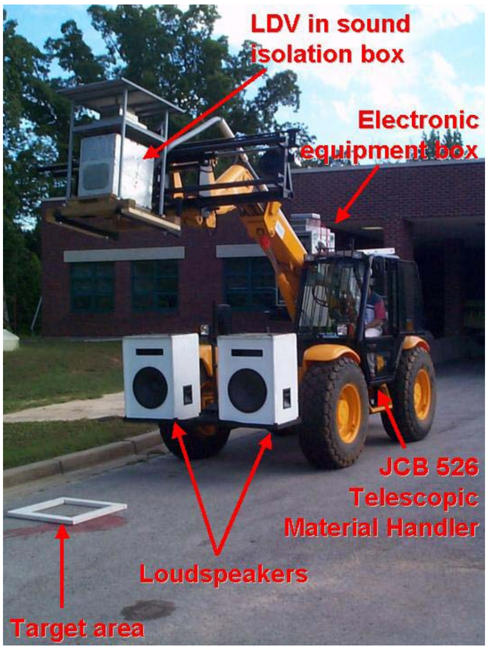


Figure 2. Photograph of the laser Doppler vibrometer-based acoustic-to-seismic landmine detection system.

A. Stop-Stare Laser Beam Mode

In the stop-stare measurement mode, the laser beam stops at each single point of a predefined grid covering a rectangular area. Fig. 3(a) illustrates a grid definition covering an area of 1 m by 1 m. The A/S coupling transfer function, or the response of the seismic motion of the ground surface to the acoustic excitation is measured accordingly. Magnitude spectra of some grid points, measured on a road patch with an anti-tank landmine buried 7.5 cm deep, are illustrated in Fig. 4. The magnitude values within a sub-band are evaluated over all of the grid points. The results can be processed to form 2D-images as shown in Fig. 3(b). When a landmine is buried within the scanned area, spatially concentrated scanning points over the target show amplified magnitude values over certain frequency sub-bands[1],[2]. The grid size and shape of those scanning points that show amplified magnitudes, and the amplification are exploited for the landmine detection procedure. The stop-stare mode using LDV has demonstrated 95% probability of detection and 0.02 /m^2 false alarm rate in a blind test [1].

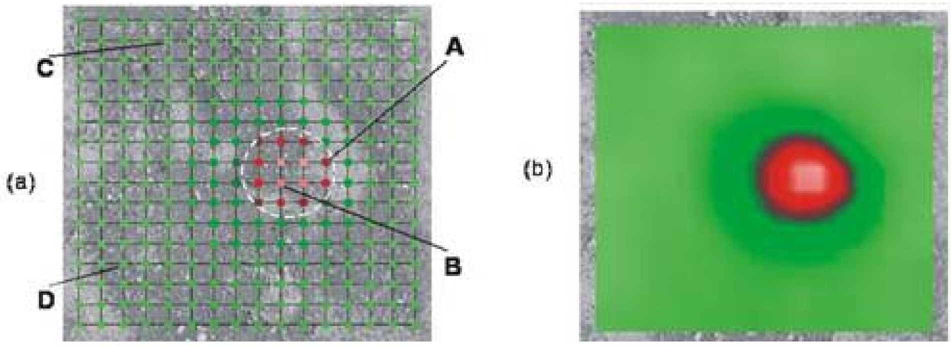


Figure 3. A grid of 16 by 16 is defined covering an area of 1m by 1m is superimposed on the image of the road in which a VS 2.2 plastic anti-tank mine is buried 7.5 cm deep. The integrated (RMS) velocity value in a frequency band between 130 Hz and 160 Hz is represented. (a) Color dots. The dot-line circle indicates the target location. In Fig. 4, individual measured magnitude spectra on points A, B, C and D are illustrated. (b) Color map, achieved from (a) in terms of interpolation and spatial filtering.

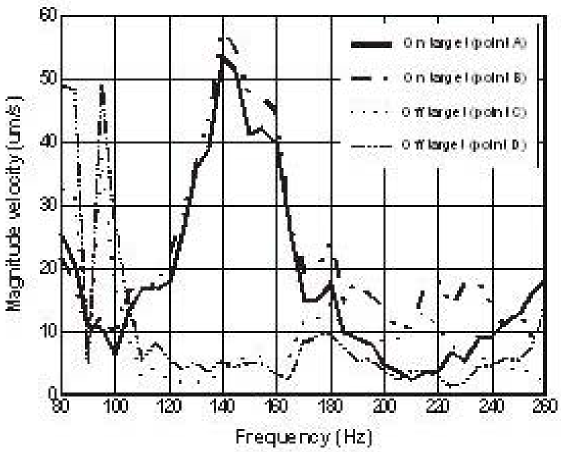


Figure 4. Measured magnitude spectra on a plastic VS2.2 anti-tank mine presented as a function of frequency at point A, B, C and D marked in Fig. 3

B. Moving Beam Mode

In order to explore the feasibility of deploying the LDV-based A/S landmine detection system on a moving vehicular platform, a feasibility study using a continuously-moving laser beam [5] from a single-beam LDV system has also been conducted. In this study, the laser beam was controlled to move continuously along a sweeping trace while measuring the instantaneous velocity of the ground surface caused by acoustic excitation. The continuous movement of the laser beam is arranged to scan a rectangular area of finite size. A similar sub-band analysis to that used for stop-stare measurements is also applicable to the moving beam measurements. The results achieved using a moving beam are comparable to those using stop-stare measurements as long as the laser beam moves at a reasonable speed. Fig. 5 illustrates a comparison between these two scanning modes. An anti-tank plastic VS2.2 landmine was buried 10 cm deep in a gravel road. Fig. 6 illustrates a systematic field study of different moving speeds (0.1 m/s, 0.5 m/s, 1.0 m/s and 1.5 m/s). An anti-tank metal M 15 landmine was buried 7.5 cm deep in the test lane. As shown in the figure, a moving speed up to 1.5 m/s could be used for detecting this type of landmine. This study indicated promise for the development of a moving vehicular platform using LDV systems.

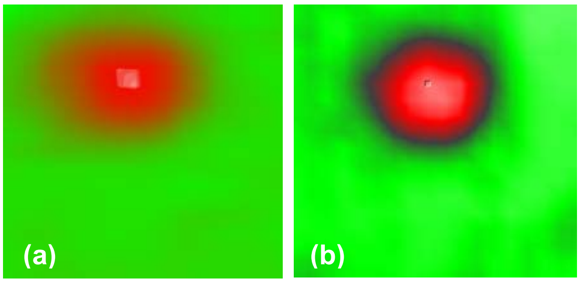


Figure 5. Scanning results analyzed between 100 – 130 Hz on a gravel road area of 60 cm by 60 cm. A plastic anti-tank landmine VS 2.2 buried 10 cm deep. (a) Moving beam scanning result at a beam speed of 0.1 m/s. In the scanning area 12 horizontal lines were defined. Target gain amounts to 5. (b) Stop-and-stare scanning results. In the scanning area a 10 by 10 grid was defined.

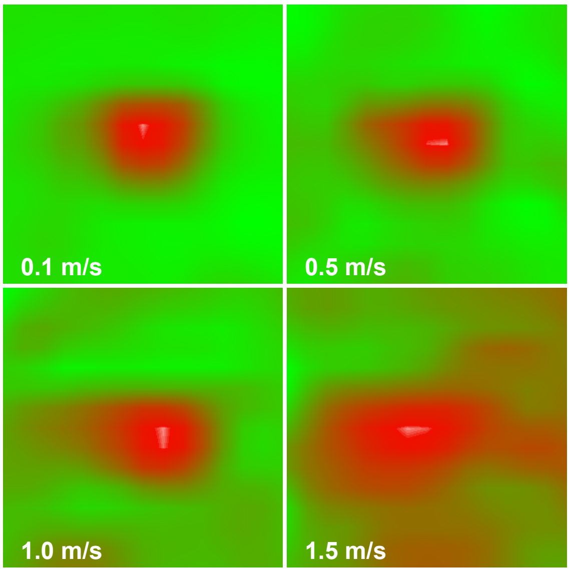


Figure 6. Moving beam scanning results at different moving speeds. An anti-tank M15 landmine buried at 7.5 cm deep in the U.S. Army Test Lane 4. 15 horizontal lines covering an area of 0.7 m by 0.7 m along with the laser beam moved at 0.1 m/s, 0.5 m/s, 1.0 m/s and 1.5 m/s. The magnitude spectra were analysized between 150 Hz and 180 Hz. The spatial resolution was 5 cm.

C. Multiple Beam LDV

Recently, a whole-field laser Doppler vibrometer using a single-laser multi-point architecture has been developed [7]. The multi-point vibrometer is based on a diode pumped solid-state laser, a diffractive optical element (DOE), and an array of fiber coupled photo-detectors. The DOE produces 16 beams from the single diode pumped solid-state laser. The 16 beams are spread uniformly across a 1-meter line over an angle of 22 degrees as shown in Figure 7, and the displacement sensitivity of each beam is better than 1 nanometer.

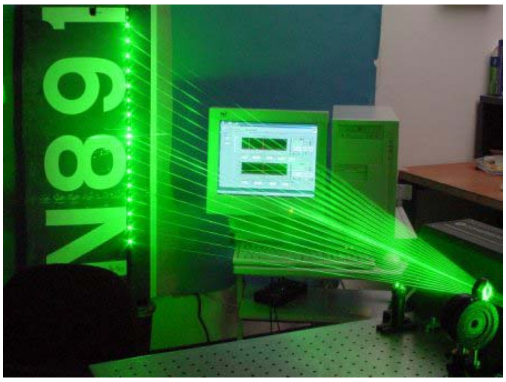


Figure 7. Beam pattern of the multiple beam vibrometer.

The Multi-Beam Laser Doppler Vibrometer has been incorporated into an acoustic-seismic confirmation sensor and tested at mine lanes under field conditions. This confirmation sensor is self-contained on an electronic vehicle and uses four custom shakers to excite the ground as shown in Figure 8. The multiple beam vibrometer is used in a continuous scanning mode to image the ground vibration. This system is capable of accurately scanning a square meter in less than 20 seconds. Figure 9 shows images antitank mines buried in off-road conditions and obscured by grass.

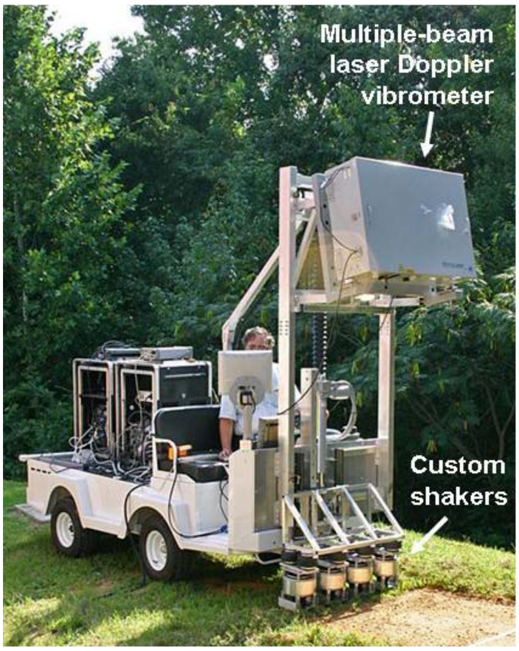
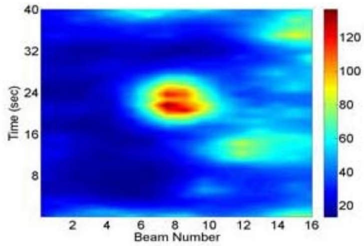
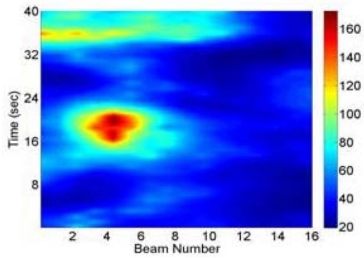


Figure 8. Acoustic/seismic confirmation sensor utilizing custom shakers for ground excitation and the multiple beam vibrometer



M19 in grass, 150-160 Hz, 0 in depth, 40 s scan



VS2.2 in 1 m tall grass, 180-190 Hz, 3 in depth, 40 s scan

Figure 9. Landmine images using the confirmation sensor shown in Figure 8.

Efforts are currently underway to develop a two-dimensional multiple beam LDV. A breadboard prototype has been constructed by the University of Mississippi and MetroLaser, Inc. that is capable of measuring 264 points in a 16 by 16 grid as shown in Figure 10. When a fieldable system becomes available, scanning time for a square meter should decrease to tenths of a second.

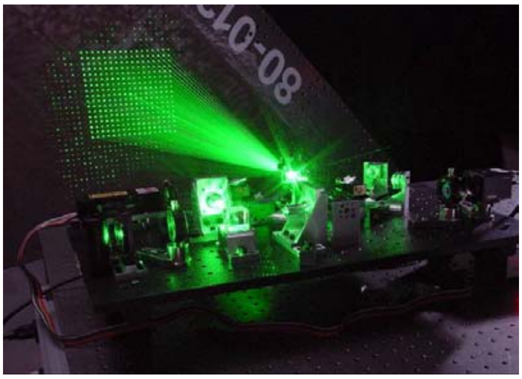


Figure 10. Prototype two-dimensional multiple beam LDV.

The sensors summarized so far are all based on the principle of laser Doppler vibrometry. The ability to sense the surface vibration in a non-contact and remote manner, the ease of controlling the laser beams for scanning a large area, and the ability to achieve a reasonable stand-off distance are major advantages of the LDV-based systems in the application of the landmine detection.

IV. ULTRASONIC DOPPLER VIBROMETER

Ultrasonic Doppler devices are much less expensive, but less standoff is achievable. A feasibility study of a low-cost ultrasonic Doppler vibrometer (UDV) is being conducted at the University of Mississippi [8]. The carrier frequency of the UDV is in the range of 50-120 kHz. Besides cost, an ultrasonic sensor offers some additional advantages over electromagnetic and laser sensors. These are: *i*) larger speckle size than that of an LDV, making an UDV virtually insensitive to horizontal target motion, *ii*) ease of tunability resulting in the ability of an UDV to penetrate through low-lying vegetation (grass, pine needles, leaves), *iii*) much lower electronics and signal processing constraints, and *iv*) direct access to the carrier signal, without the need for down-conversion electronics. A challenging task is to achieve an acceptable sensitivity of the UDV for landmine detection. For weak vibrations, the amplitude of the first-order angle-modulated sidebands is proportional to the amplitudes of the incident pressure and surface displacement, the incident frequency, the cosine of the incidence angle, and inversely proportional to the speed of sound in the medium (assumed constant and uniform).

The experimental implementation of a UDV system is shown in Fig. 11. Figure 12 presents the spectrum of a typical signal showing a carrier (120.4 KHz) angle-modulated by a surface vibrating at 150 Hz. An example of the UDV signal coming from sand vibrations induced by a buried shaker (at 150 Hz) is shown in Fig. 13, for increasing shaker excitation. The upper graph shows the UDV sideband amplitude plotted together with the LDV-measured displacement (ξ_S). It is obvious that the UDV is able to accurately follow the surface vibration characteristics measured by an LDV. In the lower graph, both sideband and carrier amplitudes are shown as a function of shaker excitation. Ambient air motion affects both UDV and LDV systems when probing vegetation-covered vibrating surfaces. Wind can move the grass blades in complex, unsteady motion. In such cases, the LDV can experience tremendous signal loss due to speckle-induced spatial decorrelation. The UDV is less sensitive to this effect.

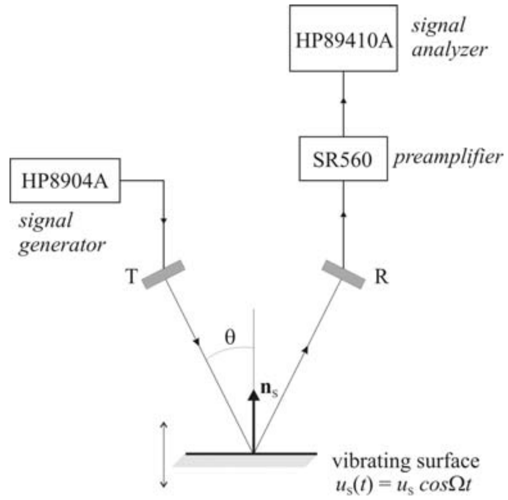


Figure 11. Schematic diagram of the experimental arrangement for ultrasonic Doppler vibrometry.

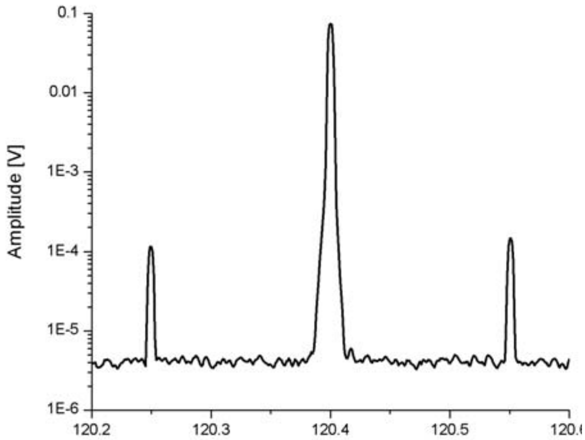


Figure 12. Typical spectrum of ultrasonic Doppler signal, showing the carrier and the 1st order sidebands.

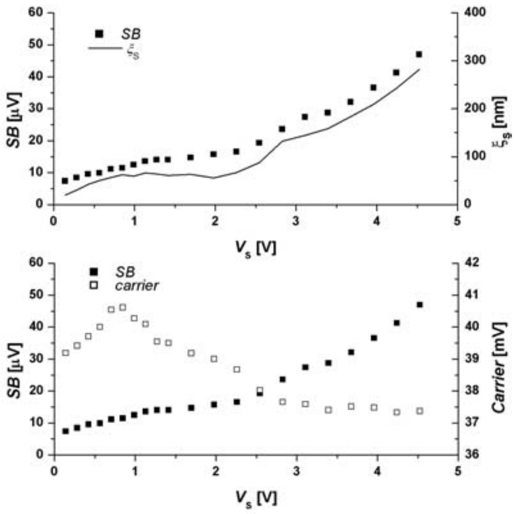


Figure 13. Comparison between UDV and LDV measuring sand vibrations above a buried shaker, for increasing shaker excitation (V_S). ξ_S denotes surface displacement amplitude (measured by LDV).

V. OPTICAL SPECKLE PATTERN INTERFEROMETER

New optical speckle pattern interferometers offer greatly reduced interrogation times for the ground surface vibrations, since a CCD camera is the central component of the device. Images of ground surface vibration behaviors of large area can be derived from a double pulse-laser illumination onto the ground. The schematic diagram for double-pulse ESPI (Electronic Speckle Pattern Interferometry) vibration sensor is shown in Fig. 14. The beam from the ruby pulse laser is split into the object and the reference beams. The object beam is expanded by a lens L1 and illuminates the object. The object is imaged onto the CCD camera by lens L2. The reference beam is overlapped with the object image onto the CCD camera producing the interference pattern. The interference pattern changes with the vibration of the object. The first interference pattern is recorded with the first laser pulse and the second interference pattern is recorded with the second pulse. These two images are stored and subtracted electronically from each other producing correlation fringes that correspond to the object vibration. Those areas of the two images where the interference pattern remains constant will give a resultant signal of zero, whereas changed areas will give nonzero signals. Figure 15 shows an example of the correlation fringe pattern of the vibrating sand with the landmine buried 2.5 cm deep.

An experimental investigation using the double-pulse ESPI sensor for acoustic landmine detection has been conducted in which mines were buried in the sand. The vibration of sand was excited by an electro-dynamic shaker. Experimental results on an anti-tank plastic VS 1.6 landmine are presented in Fig. 15. The usefulness of an optical speckle pattern interferometer in field applications is still being investigated.

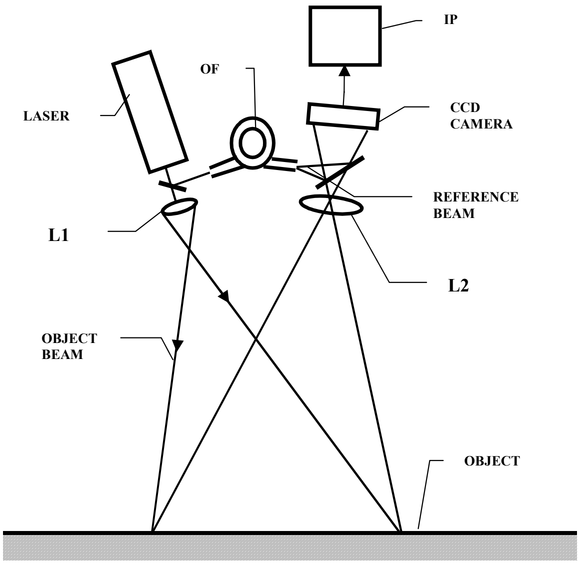


Figure 14. Schematic diagram for double-pulse ESPI vibration sensor. L1,L2-lens, OF-optical fiber, IP-image processor.

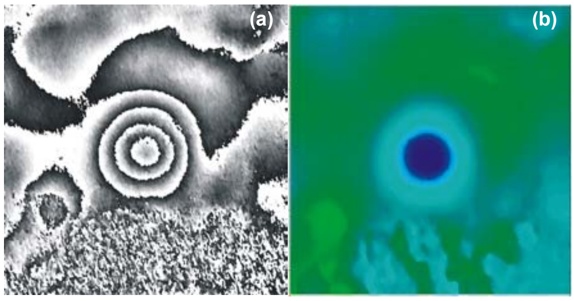


Figure 15. Images from the ESPI vibration sensor on an antitank plastic VS 1.6 landmine buried 2.5 cm deep in sand. The vibration frequency is 204 Hz. The size of the images is 0.5 x 0.5 m. (a) Correlation fringe pattern of the sand surface. (b) Pseudo-color image achieved from (a).

VI. RADAR DOPPLER VIBROMETRY

A related concept is to employ radar Doppler vibrometry (RDV) [9]. A reasonable carrier frequency of a RDV can range between several MHz and several hundred MHz. The higher the carrier frequency, the higher the achievable Doppler frequency-modulation index (which is crucial to sensitivity). A higher carrier frequency, however, brings with it a higher degree of technological challenge, and is thus more expensive.

VII. SENSORS COUPLED WITH A/S LASER SENSORS

An effort is underway to fuse the A/S technology with ground penetrating synthetic aperture radar (GPSAR) [13]. These two technologies are orthogonal and, when used in concert, significantly improve the probability of detection and reduce the false alarm rate. They function best against different types of mines under different burial conditions because they exploit disparate phenomena to detect mines. Acoustic-to-seismic coupling into the ground excites a vibration resonance in the buried landmine [10]. Extensive field tests have revealed the detection capability for shallow and plastic landmines using A/S LDV-based landmine detection technology [11] since the mechanical structure of plastic landmines facilitates resonant vibrations from A/S coupled excitation. For detecting deeply buried and metal landmines, GPSAR provides optimal detection ability [12]. Figure 16 illustrates a case in which the A/S LDV-based detection system yielded better results than that of the GPSAR. Figure 17 illustrates a case in which the GPSAR yielded better results on a deeply buried metal landmine than that of A/S LDV-based detection system. Figure 18 illustrates a case where the GPSAR yielded a false alarm while the A/S laser Doppler vibrometer-based detection system did not. These figures demonstrate the promise inherent in combining these two technologies into a single sensor suite.

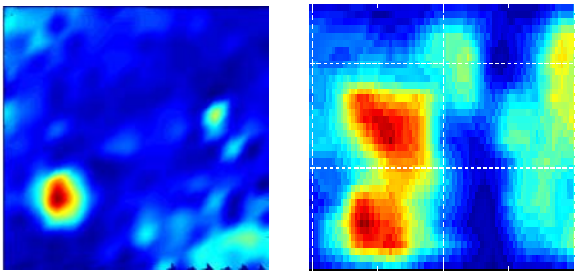


Figure 16. Comparison between images achieved from A/S lDV-based system and a GPSAR. An anti-tank VS 1.6 platic landmine buried 7.5 cm deep in the US Army test lane. Both images represent an area of 1m x 1m. Left: Scan image by the acoustic/seismic (A/S) laser Doppler vibrometer based detection system. Right: Scan image by the ground penetrating synthetic aperture radar (GPSAR).

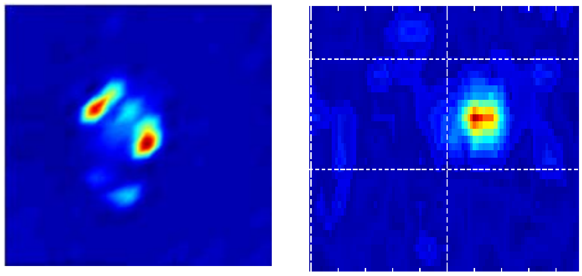


Figure 17. Comparison between images achieved from A/S lDV-based system and a GPSAR. An anti-tank M21 metal landmine buried 15 cm deep in the US Army test lane. Both images represent an area of 1m x 1m. Left: Scan image by the acoustic/seismic (A/S) laser Doppler vibrometer based detection system. Right: Scan image by the ground penetrating synthetic aperture radar (GPSAR).

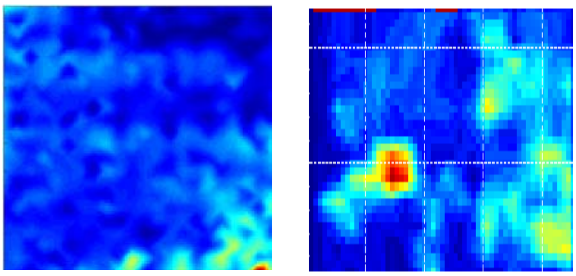


Figure 18. Comparison between images achieved from A/S lDV-based system and a GPSAR. One area with known high GPR false alarm in the US Army test lane. Both images represent an area of 1m x 1m. Left: Scan image by the acoustic/seismic (A/S) laser Doppler vibrometer based detection system. Right: Scan image by the ground penetrating synthetic aperture radar (GPSAR).

VII. SUMMARY

This paper discusses all of the vibration sensors being used or investigated for buried landmine detection by The University of Mississippi. Systematic field experimental results have been achieved for a single point scanning LDV in its stop-stare and moving beam scanning modes and for single-laser multi-point systems. Laboratory experimental results from an ultrasonic Doppler vibrometer, and from an optical speckle pattern interferometer have also been presented. Recent field experimental results using the fused system comprised of the A/S multiple LDV-based sensor and a ground penetrating synthetic aperture radar have also been discussed, which motivated a new development of fused detection sensor system with a higher probability of detection and lower false alarm rate than either technology can achieve individually.

ACKNOWLEDGMENT

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