An experimental study on antipersonnel landmine detection using acoustic-to-seismic coupling^{a)}

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An acoustic-to-seismic system to detect buried antipersonnel mines exploits airborne acoustic waves penetrating the surface of the ground. Acoustic waves radiating from a sound source above the ground excite Biot type I and II compressional waves in the porous soil. The type I wave and type II waves refract toward the normal and cause air and soil particle motion. If a landmine is buried below the surface of the insonified area, these waves are scattered or reflected by the target, resulting in distinct changes to the acoustically coupled ground motion. A scanning laser Doppler vibrometer measures the motion of the ground surface. In the past, this technique has been employed with remarkable success in locating antitank mines during blind field tests [Sabatier and Xiang, IEEE Trans. Geosci. Remote Sens. **39**, 1146–1154 (2001)]. The humanitarian demining mission requires an ability to locate antipersonnel mines, requiring a surmounting of additional challenges due to a plethora of shapes and smaller sizes. This paper describes an experimental study on the methods used to locate antipersonnel and mines in recent field measurements. © *2003 Acoustical Society of America.* [DOI: 10.1121/1.1543554]

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I. INTRODUCTION

In recent years, the proliferation of landmines in many regions of the globe has focused worldwide attention on humanitarian landmine detection. Landmines keep refugees away from their homes and displaced away from their lands long after the guns of war fall silent. They endanger those who endanger no one, fostering fear in the innocent and young. This threat of antipersonnel (AP) landmines necessitates the development of humanitarian landmine detection systems. Current conventional detectors and groundpenetrating radars rely preferentially on detecting the metallic materials contained in landmines. The constant struggle to negate the advances of the other side has led manufacturers to mass produce nonmetallic mines. This requires novel approaches to mine detection. One of the more successful approaches involves the use of acoustic waves or mechanical vibrations for penetrating or exciting the ground surface.^{1–8} While some of these approaches are still being investigated under laboratory conditions, this paper emphasizes field measurement results achieved using a laser Doppler vibrometer-based acoustic-to-seismic technique¹ to locate antipersonnel mines.

The first half-meter below an outdoor ground surface contains air-filled porous soil, which allows transmission of acoustic energy into the ground. Consequently, an acoustic signal impinging on the ground surface produces seismic motion of the surface.⁹ This phenomenon has interested researchers since the $1950s^{9-15}$ and is known as *acoustic-to-seismic coupling (A/S)*. The underlying physics of this seis-

mic motion was identified as the result of motion of air in the pores of the soil. The motion of the air couples to the skeletal frame of the soil through momentum transfer and viscous drag at the porous walls, causing its energy to then be transferred to the soil frame.^{9,13} This transfer of acoustic energy to the air-filled soil must be treated by a poroelastic wave model due to Biot,¹⁰ for example. The Biot theory admits two compressional wave solutions. The waves are referred to as the waves of the first and second types (type I and type $II^{9,10}$). The ground itself can be modeled as a twodimensional poroelastic medium of depth d overlying a semi-infinite nonporous substrate. The air-soil interface can be assumed to be a free surface and the lower interface at depth d can be assumed to be in welded contact with an impermeable membrane between the two media. The air is allowed to flow across the upper boundary while it penetrates insignificantly below the elastic medium. For this physical system, wave equations with boundary conditions can be analytically solved (see Ref. 9 for more details). It is of practical significance in this context that this layered model explains a velocity response at the upper boundary due to the incident acoustic wave that would be the result of interference between the up- and down-going waves in the layer. In the following, we refer to the velocity response on the surface of the porous ground itself to the acoustic excitation as background velocity.

Typical burial depths of AP mines are usually only a few centimeters, placing them in this porous region of the soil. When an AP mine is buried, the A/S coupled waves undergoes distinct changes and can be sensed on the ground surface. Pertaining to the humanitarian landmine detection, it is also worthwhile mentioning that Donskoy⁵ has shown that acoustic compliance of a mine is much greater than soils. He treated the mine–soil system as coupled harmonic oscilla-

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tors. Buried landmines will resonate under an excitation by the A/S coupled energy. "These resonances are due to the bending resonances of the mine casing's upper diaphragm."⁵

Since the early 1980s, both theoretical and experimental studies of A/S coupling have been conducted.^{11–15} Different types of sensors, including geophones and accelerometers, were used in the early measurements.^{13–15} A review of early experimental investigations on A/S coupling for landmine detection can be found in Ref. 4. Geophones or accelerometers are contact sensors and therefore are less useful in landmine detection practice, because a safe detector requires non-contact, remote sensing. For this purpose, a feasibility study using a laser Doppler vibrometer (LDV) was conducted in the early 1990s.¹⁶ The success of this study led to the development of an LDV-based acoustic mine detection technique.¹

The acoustic technique has been successfully applied to outdoor detection of antitank (AT) mines² found in surrogate U.S. Army mine lanes. In a blind test for detection of AT mines in which the testers did not know the location of mines or even whether mines were present, the technique achieved a 95% probability of detection and 0.03/m² false-alarm rate.¹⁷ However, AP landmine detection is more challenging due to their smaller size and the variability in mine shape, size, and construction. This has led to alterations in equipment and techniques tailored to accomplishing the humanitarian mine-detection mission by locating AP mines. In this paper, Sec. II contains a description of the experimental configuration of an acoustic system for AP mine detection, Sec. III discusses recent field test results, and concluding remarks are presented in Sec. IV.

II. EXPERIMENTAL CONFIGURATION

A. Laser Doppler vibrometer

Safe mine detection requires noncontact remote sensing. Therefore, a laser Doppler vibrometer (LDV) has been used for sensing the A/S-coupled surface motion. This experimental study employed a single-point interferometer. The LDV emitted a laser beam onto the vibrating surface of the ground area under test. The surface vibration caused a Doppler frequency shift of the reflected laser light. A photodetector sensed the backscattered light from the measuring object coming along the opposite path back into the LDV (see Ref. 18 for more details about an LDV). The photodetector then emitted a frequency-modulated (FM) signal, which transmitted the surface velocity information. After FM demodulation of the detector, the output signal voltage was proportional to the instantaneous surface velocity of the vibrating point on which the laser beam was shining.

B. Measurement setup

For detection of AP mines, A/S coupling measurements were performed using a scanning LDV (PSV 200 manufactured by Polytec PI, Inc.). Figure 1 schematically illustrates the measurement setup. The LDV system was mounted between two subwoofer loudspeakers (Peavey 118 sub 8 HC) and over a third sound source (Altec model 290-4G) on a vibration-isolated platform mounted on a JCB 526 Loadall telescopic material handler. Because the LDV system, which



FIG. 1. Schematic diagram of the measurement system used in humanitarian landmine detection. There are two mirrors (X, Y) in the laser Doppler vibrometer to deploy the laser beam along the horizontal and vertical direction, respectively.

was equipped with a video camera and X-Y scanning mirrors (see Fig. 1), was in the sound field of the speakers, the LDV system was placed inside an isolation box. A PC monitor displayed a video image of the ground surface being scanned. Prior to scanning, a measurement grid was defined and superimposed on the image of the ground surface as shown in Fig. 2. On these images, the intersection points of the grid lines represent the exact scanning positions of the laser beam on the ground surface.

Experimental results using pseudorandom noise in the frequency range between 60 Hz and 10 kHz have revealed that the optimal frequency range for AP mine detection is between 100 and 680 Hz for the three outdoor surfaces considered. On the scanned patch of ground, the C-weighted sound-pressure level ranged between 90 and 110 dB. The LDV unit was placed inside the isolation box 2.3 m above the ground and the laser beam was focused onto the surface at an angle of 10 deg from normal to the road surface. The horn loudspeaker was suspended below the LDV platform as a sound source for the frequency range between 300 and 680 Hz. The center of the horn opening was placed approximately 1.8 m above the ground and 0.8 m from the center of a scanned patch. For the frequency range between 100 and 300 Hz, two subwoofers beside the LDV were used.

The sound source radiated periodic pseudorandom noise while the laser beam was deployed to predefined grid points one by one. In responding to the acoustic excitation, the instantaneous seismic velocity of the ground surface was sampled through one data collection channel, Fourier transformed, and averaged over several periods in a complex frequency domain. A resulting complex velocity function $\tilde{V}(f)$ was obtained at each grid point.



FIG. 2. Video camera photos of two road surfaces in test lanes. The video camera is integrated in the laser Doppler vibrometer system. The rasterscanning results in forms of color grid dots were superimposed onto the video image. In each image, the photo shows an area of 69 by 51 cm. A grid of 32 by 32 points covered an area of 30 by 30 cm. (a) Gray-gravel road surface with scanned color grid dots analyzed within a frequency range between 130 and 160 Hz. A PMA 3 antipersonnel mine was buried 2.5 cm deep in test lane 4. (b) Brown-gravel road surface with scanned color grid dots analyzed within a frequency range between 340 and 370 Hz. A VS 5.0 antipersonnel mine was buried 5.0 cm deep in test lane 5.

C. Field conditions

Real AP mines and mine simulants have been buried in the test lanes for more than 3 years. Real AP mines contained the original explosive material inside the mine case; however, the detonator was removed for safety purposes. Mine simulants were filled with nonexplosive substances with dielectric properties similar to explosive material. Data collections were performed during daylight hours. Three ground surfaces in which AP mines were buried have been investigated. Two of these surface [see the photographs in Figs. 2(a) and (b) consisted of roads that were prepared by removing the existing soil and replacing it with one of two soil types. The third surface investigated was a natural soil [as shown in Fig. 6(a)]. Seismic refraction surveys, soil gradation, and sieve analysis¹⁹ were carried out on these three soil materials. Table I lists relevant soil properties. Table II lists compression and shear wave speed. These data are used to characterize the lanes and useful for future modeling.

D. Basic analysis method

The magnitude of the spectrum of the velocity function $\tilde{V}(f)$ at each grid point was integrated over a frequency band

TABLE I. Soil properties of three test lanes.

Lane	% Gravel	% Sand	% Fines	Field density	Porosity	Flow resistivity range (g.s.cm ⁻³)
Lane 4	56.0	36.0	8.0	1.54 g.cm-3	41.89%	30.64-274.88
Lane 5	21.4	56.7	21.9	1.48 g.cm-3	44.15%	283.53-1430.12
Natural soil	0.5	67.1	32.4	1.64 g.cm-3	38.11%	Not available

chosen according to the occurrence of consistent amplifications in magnitude velocity in the presence of a mine

$$M_{ij} \int_{f_1}^{f_2} |\tilde{V}_{ij}(f)| df, \qquad (1)$$

with f_1 , f_2 denoting the lower and upper frequency limits, respectively. *i*, *j* was the subscript of a grid point on the *i*th row and *j*th column of the grid. In this way, a single-valued magnitude velocity could be presented as data points on a color dot map.

An example of a scanning result is shown in form of a color dot map in Fig. 3(a), which is a cut from Fig. 2(a). This scanning result was obtained from field measurements on a gray-gravel road. Colors were automatically assigned proportionate to the integrated values of magnitude velocity in the map. The map was superimposed onto the video image of the ground surface. The circle on the color dot map indicated the mine location. Based on integrated magnitude values at individual scanning points, processing in terms of nearestneighbor and spatial filtering using two-dimensional median filter²⁰ yielded a smoothed color map as shown in Fig. 3(b). Its 3D presentation is illustrated in Fig. 3(c).

III. DISCUSSION OF MEASUREMENT RESULTS

Using the measurement setup and the analysis method described in the previous section, field measurements and subsequent analysis were performed on buried AP mines at the test lanes (see Table I). This section discusses some relevant issues of the LDV-based A/S coupling AP mine detection based upon the results achieved from the field tests.

A. Detection of buried landmines

Figure 4 shows several magnitude spectra of velocity functions on and off the target for the PMA 3 AP mine that is 10 cm in diameter, buried 2.5 cm deep at test lane 4 (listed in

TABLE II.	Compression	and s	shear	wave	speed	of	three	test	lanes
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	Compression	n wave (P-wave)	Shear wave (S-wave)			
Lane	Layer speed (m/s)	Averaged depth (m)	Layer speed (m/s)	Averaged depth (m)		
Lane 4	274	0	84	0		
	526	0.3	150	0.11		
	716	0.82	260	0.33		
Lane 5	320	0	90	0		
	533	0.1	260	0.27		
	693	0.78	340	1.7		
Natural soil	259	0	38	0		
	472	0.06	274	0.15		
	693	0.6	•••			



FIG. 3. A grid of 32 by 32 points was defined by covering a scanned patch of 30 by 30 cm (spatial resolution: 0.97 cm) in lane 4. A PMA 3 antipersonnel mine with a circular shape was buried 2.5 cm deep. The integrated velocity value in the frequency range between 130 and 150 Hz is presented. (a) Color dots. The circle indicates the target location. On points A, B, C, and D individual measured magnitude spectra were illustrated in Fig. 4. (b) Color map achieved from (a) in terms of image processing. (c) Threedimensional color presentation derived from (b). (d) Photograph of a plastic PMA 3 antipersonnel mine that was 10 cm in diameter.



FIG. 4. Magnitude velocity spectra evaluated from the scanning result shown in Fig. 3. Individual magnitude velocity spectrum evaluated from the grid points A, B, C, and D indicated in Fig. 3(a).

Table I). Frequency resolutions of 2.5-10 Hz were often used to represent the discrete velocity functions $\tilde{V}(f_i)$. The magnitude spectra on top of the target indicate that the A/S coupled energy excites resonant vibrations in the buried AT landmines (see also Refs. 5 and 6). In Figs. 3(a) and (b), a region of interest could be identified in both presentations, indicating the presence of a mine. The size of the mine could be estimated by counting grid points [in Fig. 3(a)] across the region. When a region of interest was thought to indicate a mine, the middle of the region was assumed to be associated with the center position of the buried mine. The laser beam could then be moved to a point in that region, thereby marking the location on the ground. It usually pointed to the center of the mine with a radial accuracy of less than 2 centimeters. Accuracy was significantly enhanced through the use of closer grid-point spacing.

Mine types, burial depth, and ground surfaces predominated in determining A/S coupling responses of ontarget velocity. Field measurements have shown that the maximum ratio between on- and off-target velocity in a suitable frequency band could range from multiples of 10 down to 2.

B. Background velocity

Road types (depending on the construction material), deep ground layering, and weathering conditions influence A/S coupling responses of off-target velocity, henceforth referred to as background velocity responses. As shown in Fig. 4, the detection of mines depends upon exploiting the difference between the ground velocity over a mine and away from a mine. Therefore, evaluations of background velocity functions are important for detecting landmines. Using the brown-gravel road at test lane 5 as an example, Fig. 5 illustrates background velocity functions both within a single $0.36 \text{ m}^2 (0.6 \times 0.6 \text{-cm})$ patch and across six similar patches distributed randomly along the road. The standard deviation



FIG. 5. Background magnitude velocity spectra in the brown-gravel road. The standard derivation of the velocity is shown as error bars for each frequency. (a) Averaged background magnitude velocity spectrum evaluated from five individual spectra. The individual background magnitude velocity spectra are randomly selected within a single 60- by 60-cm patch. (b) Averaged background magnitude velocity spectra evaluated over six (60- by 60-cm) patches.

of the velocity is shown as error bars for each frequency. At a given acoustic excitation in a range around a C-weighted sound level of 100 dB, the averaged velocity assumes lower values of 6–10 μ m/s in the frequency range between 100 and 300 Hz and higher values of about 15–30 μ m/s between 450 and 680 Hz. One sharp peak at 320 Hz has been identified as being caused by the LDV mirror resonance frequency. Another sharp peak at 390 Hz has been identified as emanating from the first room mode of the sound isolation box covering the LDV. When a number of scanned points on the ground assume clearly higher velocity values than the background velocity, the differences between on- and off-target velocities are mapped on the scanning image as regions of interest.

C. Spatial resolution

The spatial resolution of scanning is of vital importance for mine detection, especially since the variability of mine sizes and shapes is relatively large among AP mines. Based on finding the consistent amplifications of the magnitude ve-



FIG. 6. Scanning result on a combination of antitank and antipersonnel landmines. A plastic VS 2.2 antitank mine, 24 cm in diameter, was buried 6 cm deep surrounded by three plastic antipersonnel mines (one TS 5.0 mine on opposite sides of the antitank mine and one VS 5.0 on a third side). These three antipersonnel mines, 9 cm in diameter, were buried 3 cm deep. A grid of 49 by 49 points covering an area 1.1 by 1.1 m was defined, resulting in a spatial resolution of 2.3 cm. (a) Relative positions of the mines before burial in the natural soil. (b) The scanning results in a three-dimensional presentation. Magnitude spectra were integrated within the frequency range between 100 and 300 Hz.

locity over a certain frequency range, an adequate spatial resolution under ideal field conditions has to obey the spatial Nyquist sampling principle. This requires that at least two grid points along the minimum dimension on top of a mine be included. Moreover, a spatial oversampling protocol allows visual recognition of target shape, estimation of the target size, and, therefore, can distinguish mines from background clutter. Clutter may result in high magnitudes of velocity attributable to such causes as inhomogeneity of the ground. Figure 3 illustrates scanned results with a spatial resolution of 1 cm. As expected, the target images are circular in shape due to spatial oversampling. Clutter often causes irregular-shaped and smaller-sized images in the color maps. The spatial oversampling, however, results in longer detection time.

Figure 6 shows a combination of antitank (AT) and AP mines. A VS 2.2 AT mine, 24 cm in diameter, was buried 6 cm deep surrounded by three AP mines (two TS 5.0 mines on opposite sides of the AT mine and one VS 5.0 on a third side). These three AP mines, 9 cm in diameter, were buried 3 cm deep. All these four mines were made of plastic. Figure



FIG. 7. Scanning results in form of a color map on a PMD 6 antipersonnel mine buried 5 cm deep. Its rectangular shape has a (top view) length of 20.5 cm and a width of 9 cm. A grid of 32 by 32 points covering an area 30 by 30 cm was defined, resulting in a spatial resolution of 1 cm. Magnitude spectra were integrated within 280–310 Hz.

6(a) shows the relative positions of the mines before burial. To resolve an image of the smaller size of AP mines, a grid of 49 by 49 points covering an area 1.1 by 1.1 m was defined, resulting in a spatial resolution of 2.3 cm. Figure 6(b) illustrates the scanning results in a three-dimensional presentation. Magnitude spectra were integrated within the frequency range between 100 and 300 Hz. As one can see, one AT mine surrounded by three AP mines could be clearly resolved with the chosen spatial resolution.

Figure 7 shows results scanned on a PMD 6 AP mine buried 5 cm deep. Its case is a wooden box. Its rectangular plan form has a (top view) length of 20.5 cm and a width of 9 cm. A grid of 32 by 32 points covering an area 30 by 30 cm was defined, which resulted in a spatial resolution of 1 cm. Magnitude spectra were integrated within a frequency range between 280 and 310 Hz. The mine image presented an elongated shape even though its rectangular shape could not be resolved by the chosen spatial resolution.

Figure 8(a) shows results for a VAL 69 AP mine buried 5 cm deep. Figure 8(b) shows a photograph of the mine. In the plan view, the diameter is 14 cm. A grid of 32 by 32 points covering an area 30 by 30 cm was defined, which resulted in a spatial resolution of 1 cm. Magnitude spectra were integrated within a frequency range between 360 and 400 Hz. Due to the irregular shape of the top of this mine, the scanned results tended to show an irregular image.

D. Frequency resolution and analysis

A/S coupling responses for AP mines often presented amplifications over a broad frequency range, as the example in Fig. 4 shows. The integration of the magnitude velocity spectrum for each scanning grid point was performed within a narrow frequency band using Eq. (1). A color map representing the integrated magnitude velocity values over the entire grid was then formed. This narrow-band procedure



FIG. 8. (a) Scanning results in the form of a color map. A grid of 32 by 32 points was defined covering an area of 30 by 30 cm resulting in a spatial resolution of 0.97 cm. Magnitude spectra were integrated between 360 and 400 Hz. Due to irregular shape at the top of this mine, the scanned results tended to show an irregular image as well. (b) Photograph of a VAL 69 antipersonnel mine. The largest circular diameter is 14 cm.

(b)

was repeated by stepping through the entire frequency range with an overlap from one frequency band to the next. Figure 9 illustrates the narrow-band analysis of scanning results obtained on a VS 5.0 mine buried 5 cm deep in test lane 5. By stepping a narrow frequency band with a 30-Hz bandwidth through the frequency range between 240 and 370 Hz, the mine image remained in the same position with almost the same size, while a smaller clutter image could only be seen in the band between 280–310 Hz and 340–370 Hz.

The narrow-band analysis was based on an adequate frequency resolution (spacing) in the data. Higher frequency resolution or smaller frequency spacing facilitated broader possibilities to optimize the narrow-band analysis. The con-



FIG. 9. Narrow-band analysis of scanning results obtained on a VS 5.0 mine buried 5 cm deep in the brown-gravel road. By stepping a narrow frequency band with a 30-Hz bandwidth through the frequency range between 240 and 370 Hz, the mine image remained in the same position with almost the same size, while smaller clutter could only be seen in the band between 280–310 Hz and 340–370 Hz.

sistency in the position and the size of a target, while stepping a narrow-band filter through a relative broad frequency range, enhanced distinguishing mines from background clutter. Higher frequency resolution, however, required collecting a larger number of data points. In the experimental study we chose a resolution in order of 2.5–10 Hz that had to be predefined for the data collection. Both the spatial and frequency resolution determined the speed of scanning. Taking an example as shown in Fig. 3, 32 by 32 scanning points covered an area of 30 by 30 cm. A frequency resolution of 10 Hz was used at a sampling frequency of 1.024 kHz, yielding a signal period of order of 100 ms. Using three averages the scanning took about 5–10 min. A detection system with multiple laser beams and parallel processing will increase the scanning speed.

E. Clutter responses

Loose soil and inhomogeneities at a shallow depth in the ground can lead to high magnitude in the A/S coupling responses. Figure 10 illustrates scanning results for an VS 5.0 mine buried 5 cm deep in test lane 5. In the frequency range between 420 and 460 Hz the mine appears as a single circu-



FIG. 10. Scanning results in form of color maps on a VS 5.0 mine buried 5 cm deep in the brown-gravel road, in the frequency range between 420 and 610 Hz with a frequency resolution of 5 Hz. A grid of 42 by 42 points covering an area of 50 by 50 cm resulted in a spatial resolution of 1.2 cm. Within this frequency range, there are two regions of interest. One region on the lower-left side was identified as mine response. The region on the upper-right side with an irregular shape was due to clutter.

lar region with two other clutter images in smaller amplitude. In the frequency between 450 and 520 Hz, two regions of interests could be found. The region on the lower-left side was associated with the mine response. The more irregularshaped region on the upper-right side was clutter. Figure 10 demonstrates difficulties in distinguishing mines from clutter since clutter can result in similar magnitude responses in the same frequency ranges with comparable sizes to a mine [see Figs. 10(c) and (d). When stepping the narrow-band filter to 570-610 Hz, a ring-form pattern caused by the buried AP mine appeared in the map [Fig. 10(d)]. The ring-form pattern happens at a frequency pointed out by Yu et al.²² where the soil-mine system⁵ shows an "antiresonance" at which the surface vibration of certain regions on top of the mine becomes lower than those around the mine. Figure 11 illustrates representative magnitude spectra on and off the target. The magnitude spectra on the top of the mine show distinct



FIG. 11. Magnitude velocity spectra scanned in the brown-gravel road where a VS 5.0 AP mine was buried 5 cm deep. In the frequency range between 580 and 605 Hz the magnitude spectra on the top of the mine become clearly lower than those away from the mine. In this frequency range, the mine manifests itself as a ring-form pattern in the magnitude velocity map [as shown in Fig. 10(c)].

resonant behavior in the frequency range between 350 and 410 Hz as well as 430 and 480 Hz. In addition, the on-target magnitude spectra become so small to be clearly lower than those away from the target (background) in the antiresonance frequency range between 580 and 605 Hz. These phenomena cannot be observed on the regions of the clutter.

This section has discussed some relevant issues about the AP mine detection based on the field test results. In order to perform mine detection using A/S coupling, the surface velocity on an AP mine should be clearly higher than the background velocity within a broad frequency range. Field measurements have shown that the maximum ratio between on- and off-target velocity in a suitable frequency band ranged from several multiples of 10 down to 2 due to the mine resonance. A spatial oversampling supported the recognition of target shape and size and thus enhanced the detectability of AP mines. Narrow-band frequency analysis has been found to be a good tool to enhance the detectability. When stepping a narrow-band filter through the overall frequency range, mine images remain relatively stable while clutter often causes high variability in object shape, size, and position. The resonance and antiresonance behavior of the mine-soil system²² can also be exploited to help distinguish mines from clutter.

IV. CONCLUDING REMARKS

The porous nature of the ground permits landmine detection based upon the distinct changes of the acoustic-toseismic coupled motion on the ground surface. This led to development of a new technique for humanitarian landmine detection: the laser-Doppler vibrometer-based acoustic landmine detection system. The current acoustic landmine detection system utilized a scanning single-beam laser Doppler vibrometer for sensing the acoustic-to-seismic coupled motion on the ground surface. Complex surface velocity functions of frequency were measured using a remote, rasterscanning technique. In general, the magnitude of the velocity function was used to detect antipersonnel landmines. The scanning results were evaluated within a frequency range between 100 and 680 Hz. Color maps were formed to image mine location, size, and shape. Landmine responses were found to be broadband in nature. A landmine was determined to be present when there was consistent amplification of the magnitude velocity over a relatively broad frequency band and when a circular shape in the scanning image remained intact when stepping through the overall frequency range with a narrow-band filter. Often clutter entered and exited the image as the narrow bands were sequentially changed. Sometimes clutter was also broadband. In these cases, the size of the region of interest was exploited for a decision in addition to the circular shape. For humanitarian landmine detection, the acoustic system has demonstrated a capability for detecting antipersonnel landmines buried in the subsurface of the ground with a high probability of detection. The primary challenge is to maintain a low false-alarm rate while retaining this high probability of detection. In the frequency range in which most antipersonnel mines result in amplified magnitude velocity spectra, some clutter and anomalies can also appear. In addition to the shape and size criteria, the AP landmine detection relies on recognition and identification of the resonant behavior of the soil-mine vibration system to distinguish them from the clutter and anomalies. Extensive collection of field results on broad ranges of burial AP landmines along with soil types and systematic analysis of mine signatures will promote our knowledge on enhancing the detection ability.

Up to the current time, the research effort has focused on demonstrating the feasibility of this technique in field measurements rather than achieving a high scanning speed. In the near future, efforts are expected to model the physics of the soil–mine vibration system excited by the acoustic/seismic coupling,²³ to collect and identify unique acoustic-to-seismic coupling signatures of antipersonnel landmines, systematically analyzing clutter responses. Efforts will also be made to increase the speed²⁴ and detection performance²⁵ of the current technique and to automatically recognize targets.²⁶

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