Appendix C

INFRARED/HYPERSPECTRAL METHODS (PAPER I)

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Electro-optical (EO) sensors, which include both infrared bands and hyperspectral sensors, are attractive candidates for some mine detection tasks because they can be used from a considerable standoff distance, they provide information on several mine properties, and they can rapidly survey large areas. Their ability to detect mines has been recognized since the 1950s [1]. These sensors respond to electromagnetic radiation in a sensor-specific wavelength range. The source of the received signal may be either natural (i.e., thermal emission from the target or scattering of sunlight) or artificial (e.g., a laser illuminator), which leads to both active and passive sensor concepts. Antipersonnel mines may be buried or surface-laid. Detection of surface mines, which is a trivial matter for a nearby human observer, is of interest in wide-area search operations using airborne sensors.

In spite of their long history, there is little compelling performance data available for EO detection of antipersonnel mines. Two likely reasons for this are as follows: First, EO mine signatures tend to be highly dependent on environmental conditions, which complicates data collection and performance assessment. Indeed, a number of multisensor mine detection systems have included an EO sensor (typically, a thermal imager) but have not used it because of unreliable data quality. As a result, much of the work to date comprises concept demonstrations and studies of specific phenomena. Second, the only EO performance tests involving statistically meaningful sample sizes have been conducted on U.S. Army test sites containing primarily antitank mines. Detection of antipersonnel mines is significantly more challenging than detection of antitank mines, and performance results for the two cases are not easily related. Furthermore, much of the recent work addresses detection of surface-laid antitank minefields. Minefield detection is typically much easier than detection of single mines because of the large number of mines involved and the additional spatial information (e.g., the presence of a spatial pattern). Some data have been acquired at mixed antipersonnel/antitank test sites in the United States, but scores for the two mine classes are typically not reported separately. Significant European research in antipersonnel mine detection is under way, but test sites commonly used in those efforts [2,3] are smaller.

Both thermal emissions and surface-scattering phenomena contribute to EO mine signatures, and the relative importance of these phenomena depends on whether the mine is deployed on the surface or is buried. The discussion that follows is organized first by mine deployment, and then by detection approach. References to relevant performance data are provided when available, as are specific limitations. Recommendations for research and development (R&D) programs that span several sensor concepts are presented at the end of this appendix.

BURIED MINES

Detection of buried antipersonnel mines comprises a very challenging problem. A number of concepts have been examined for this problem.

Passive Thermal Detection

Physical Basis. A large part of the solar energy incident on soil is absorbed, leading to heating. As a result of this heating, the soil emits thermal radiation detectable by a thermal infrared (IR) sensor. Natural solar heating and cooling over a diurnal cycle tend to affect a buried object and the surrounding soil differently, which leads to a detectable temperature difference. For a buried mine this difference arises because the mine is a better thermal insulator than the soil. During the day, the thin layer of soil over the mine tends to accumulate thermal energy because the mine impedes the transport of that heat deeper into the ground. As a result, soil over a mine will tend to be warmer than the surrounding soil. Conversely, in the evening hours, the soil layer over the mine gives up its thermal energy more rapidly than the surrounding soil and it appears cooler. Twice daily the soil over the mine and the background soil will assume the same temperature, making thermal detection impossible. The temperature difference and its temporal behavior depend strongly on a variety of variable natural phenomena, including the time of day, prior solar illumination, wind speed, ground cover, and soil composition (e.g., moisture content).

Most thermal detection concepts involve single looks (“snapshots”) of the region of interest. The soil over a mine has different thermal dynamics than homogeneous soil and, as a result, a time sequence of images can often produce better detection than a single image. Hence, staring sensors, which are impractical for many military scenarios, may be attractive for humanitarian demining.

Development Status. Broadband passive sensors at IR wavelengths are mature and available commercially from several vendors. Algorithms for mine detection, another critical part of any detection system, are somewhat less mature, although a number of groups have reported progress in his area.

Current Performance. As noted, compelling performance data for EO detection of antipersonnel mines are limited. Receiver operating characteristic (ROC) curves for thermal IR detection of a mixture of antipersonnel and antitank mines were reported by Baertlein and Gunatilaka [4], but those results comprised only 27 mines (examined under poor environmental conditions), of which roughly half were antipersonnel. Data from the TNO (Netherlands Organisation for Applied Scientific Research) mine lanes in the Netherlands were examined by Milisavljevic et al. [5], and performance results are reported therein for 15 antipersonnel mines. Additional results involving 18 antipersonnel mines were reported by Chen et al. [6]. In that work the data collection extended over several hours, and temporal processing was used to improve performance. Limited results on thermal IR detection of buried antitank minefields from airborne sensors are summarized in Miles, Cespedes, and Goodson [17].

Limitations. Signature variations with time and environmental conditions are a persistent problem for thermal IR mine detection. The optimum time for detection and the expected contrast depend on factors noted above that are often unknown to a remote observer. Surface clutter from reflected light and inhomogeneous soil properties are also problematic. In many cases the size of these clutter artifacts is comparable to that of antipersonnel mines, which leads to false alarms. Thermal emission from foliage (at the temperature of living, respiring vegetation) tends to mask the temperature of the underlying soil (and the thermal mine signature).

Potential for Improvement. The processes that produce thermal IR target signatures and clutter are poorly understood. In some cases, good detection performance has been demonstrated, but when such systems fail, the reasons for failure are often not evident. A better understanding of target and clutter signatures could substantially improve their effectiveness by allowing them to be deployed appropriately. Staring sensors should also be considered, which take data over an extended period in time, waiting for favorable conditions to arise. Time-history information will also help to compensate for the variability of thermal signatures with time and environmental conditions.

Active Thermal Detection

Physical Basis. Passive thermal detection is based on solar heating of the soil, and it is prone to fail when environmental conditions are not conducive. Active analogs of the process have been investigated, in which intense optical [7,8] or high-power microwave (HPM) [9–11] sources are used. Soil has a low optical albedo and a moderately high radio frequency conductivity, both of which lead to effective heating by external sources. In contrast, the mine is typically either plastic (a good electrical and thermal insulator) or metallic (a good electrical and thermal conductor). The HPM approach to heating is particularly attractive because an HPM antenna can be shared by a ground-penetrating radar (GPR). In addition to the thermal effects of HPM, the presence of the mine manifests itself in another way: The mine's dielectric discontinuity produces reflections of the illuminating microwave field (a "standing wave pattern"), which affects HPM absorption and heating.

Development Status. The investigation of this approach has not progressed beyond small-scale experiments. Progress is not significantly hampered by the instrumentation. Suitable optical and HPM sources are available, and the thermal IR sensor required here is identical to that described in the previous paragraph.

Current Performance. Controlled demonstrations using heat lamps [7], lasers [8], microwaves [9,10], and two-frequency microwaves [11] have been presented, but only a few mines were imaged. No performance data are available.

Limitations. Relatively long exposures (up to 12 minutes in Storm and Haugsted [7]) are required to heat the soil, and the peak contrast may not be observed for several minutes after heating, but suitable operational concepts could be defined to make this detection paradigm practical. The HPM approach is somewhat better developed than the optical approaches. The key issues are (1) producing uniform illumination on a rough ground, (2) producing sufficient power to heat the ground at a distance, and (3) avoiding the human health hazards associated with HPM.

Potential for Improvement. The ability to generate a new sensor paradigm by simply adding an HPM source to an existing GPR system is attractive. Studies of this detection concept are incomplete, but the dynamics of the thermal processes suggest that it is impractical for rapid area scans. Additional research will be required to determine the limits of the method.

Passive Detection of Nonthermal Surface Phenomena

Physical Basis. Buried mines are also detectable via soil disturbances and vegetation stress. Soil comprises a mixture of materials having a range of particle sizes. Natural processes tend to move the smaller particles deeper into the soil. Excavation for mine burial brings the smaller particles to the surface, where they affect surface scattering. The most effective sensors of this behavior are hyperspectral, although polarimetric effects have also been alleged. Because it obscures the surface, vegetation presents additional challenges to buried mine detection, but another phenomenon can be exploited in this case. The mine presents a moisture barrier to the upward and downward flow of soil water. This leads to a (temporary) pooling of water over the top of the mine after a period of rain and drier soil over the mine in the absence of rain. The latter condition tends to produce drought stress on the vegetation, which can be detected with a hyperspectral sensor.

Development Status. A large-scale experimental collection of the underlying hyperspectral signatures (0.35–14 μm) for soil and buried mines was performed by Veridian-ERIM [12], with a subsequent analysis by Kenton et al. [13]. An outdoor surface mine collection using a nonimaging spectrometer was reported by Haskett et al. [14]. A hyperspectral imaging visible/near infrared (VNIR) sensor has been flown on an airborne platform by the Canadian Defence Research Establishment–Suffield (DRES) [15]. The U.S. Marine Corps developed the Coastal Battlefield Reconnaissance and Analysis (COBRA) system [16], which employs a multispectral camera (VNIR) on an airborne platform.

Current Performance. Performance data for 18 mines buried under three soil types are reported by Haskett et al. [14]. Limited performance data are reported in McFee and Ripley [15] for buried antitank and antipersonnel mines under a variety of ground covers. Those data were acquired after the mines had been in place for some time. The antipersonnel mine detection performance was encouraging, but the sensor was hampered by insufficient resolution for these smaller mines. Detection of minefields, portions of which were underwater, is discussed in Stetson et al. [16] for the COBRA system.

Limitations. A number of challenges are encountered in nonthermal detection of buried mines. The effect of the soil disturbances described above is transient and is greatly reduced by rainfall. Vegetation stress also depends on recent rainfall, but it is also a longer-term effect, which may not be evident for recently buried mines. Both phenomena are unreliable in areas with broken grass or low shrubs, which present false alarms.

Potential for Improvement. The findings of McFee and Ripley [15] bear further study. A hyperspectral sensor with high spatial resolution should be developed for antipersonnel mine detection.

Active Sensing of Nonthermal Surface Phenomena

Physical Basis. Active hyperspectral or polarimetric sensing of the phenomena described in the previous section are also feasible for buried mines. This approach circumvents the problem of uncontrolled, variable solar illumination by using a scanned laser illuminator. An accompanying narrowband receiver can be used to reject ambient light, thereby improving image contrast.

Development Status. From 1987 to 1992, the U.S. Army developed the Remote Minefield Detection System (REMIDS) [17] as part of the Standoff Minefield Detection System (STAMIDS). REMIDS comprises an airborne sensor package using both active polarimetric and passive thermal sensors. The system was used in field tests at Fort Hunter-Liggett, Calif., and Fort Drum, N.Y., in 1990–1991. This technology formed the basis for the Airborne STAMIDS (ASTAMIDS) program [18], which was field-tested during 1996.

Current Performance. The REMIDS sensor has been tested against both surface-laid and buried mines. A summary of the performance against antitank minefields is presented in Miles, Cespedes, and Goodson [17]. Limited results from the ASTAMIDS sensor are summarized in [19] for buried and surface-laid antitank minefields. Buried mine detection performance was limited.

Limitations. Some relevant issues are noted in the previous Limitations subsection. The detection range of active sensors is also necessarily limited by the transmitter power.

Potential for Improvement. Prior work with active polarimetric sensors (REMIDS) for buried antitank mines has been disappointing. To date, there does not appear to have been a study of hyperspectral sensors for this application. The modest successes described above in Passive Detection (under Current Performance) should be explored for active detection of antipersonnel mines using a suitable spatial resolution.

SURFACE MINES

As noted, surface mine detection is primarily of interest for airborne or other platforms with an appreciable standoff distance. At large distances, the number of pixels on the mine decreases, but some compensating factors exist. First, the surface scattering properties of the mine are detectable in addition to thermal phenomena. Second, whereas the thermal signatures of buried mines often have indistinct shapes, the shapes of surface mine signatures contain significant information and may be useful discriminators. Finally, when the illumination arrives at low elevation angles, shadows may also be exploited in detection.

Passive Thermal Detection

Physical Basis. Because a mine's thermal properties are considerably different than those of vegetation, a solar-heated mine viewed with a thermal IR sensor typically has a high contrast. This contrast often exists even when the mine is painted to camouflage its presence. Differences in paints or coloration on different parts of the mine (e.g., the central trigger assembly vis-à-vis the main body) may lead to complex, distinctive thermal signatures because of different solar absorptions.

Development Status. The U.S. Department of Defense has developed several IR minefield detection systems for airborne and vehicle platforms, including the REMIDS and ASTAMIDS systems. As noted previously, those systems have been principally used against antitank mines. Another more recent development is the U.S. Army Lightweight Airborne Minefield Detection (LAMD) system, in which both passive thermal IR and active polarimetric near infrared (NIR) sensors will be used against surface antitank mines. The development of an interim system is reported in Trang [20].

Current Performance. Information on thermal IR detection performance for surface-laid antipersonnel mines is not available in the literature, but there are significant data on antitank mine detection. The performances of some airborne thermal sensors of surface minefields are reported in Stetson et al. [16]. ROC curves for detection of surface antitank mines using a thermal IR sensor were reported in selected reports [20–22].

Limitations. With due attention to the increased role of surface scattering and the more rapid time-dependence of surface mine heating, the limitations noted above for buried mine detection are also relevant here.

Potential for Improvement. As noted for buried mines, there is a need to better understand the signatures and their relation to environmental conditions. Knowledge of the sun angle could be used to predict heating patterns, which may improve detection and false alarm rejection.

Passive Nonthermal Detection

Physical Basis. The surface scattering properties of mines are distinct from those of soil and vegetation, particularly when measured in the spectral domain, and that spectral dependence can be a powerful discriminator. In addition to their spectral properties, many mines are relatively flat and covered with the same material over much of their top surface. This leads to the appearance of a uniform region in the imagery, which tends to be useful in image processing. The polarization properties of surface-laid mines can also be exploited by a passive sensor. The polarimetric signature of unstructured random surfaces such as grass tends to be random itself, which leads to an unpolarized return. In contrast, the smooth surfaces of man-made materials tend to produce a polarized signature when viewed at low elevation angles. Polarimetric signatures can exist even where there is no detectable thermal signature.

Development Status. Detectors of passive broadband polarimetric emissions have been described by the Defence Evaluation and Research Agency (DERA) in the United Kingdom [23], by Larive et al. in France [24], and by Cremer et al. in the Netherlands [25], all of which are based on commercial mid-wave infrared (MWIR) cameras. The DERA system, developed by Nichols Research in the United States, uses a micropolarizer array bonded to the focal plane array. The French and TNO systems use uncooled rotating wire-grid polarizers in front of the sensor. The DERA system has been used in vehicle-mounted data collections, and work on the data processing algorithms has been described. The TNO system has been used for tests over a diurnal cycle while staring at emplaced mine surrogates. Significant progress was reported in modeling the signatures. A passive imaging, hyperspectral, polarimetric sensor has been demonstrated by Iannarilli et al. [26]. The sensor was used to image mine surrogates, and techniques for data analysis were presented. Airborne detection of surface minefields has been demonstrated by the DRES hyperspectral system [27]. That test involved approximately half antitank and half antipersonnel mines.

Current Performance. Few detection performance estimates are available for passive nonthermal detection of antipersonnel mines. DRES [27] reported the performance of ground-based and airborne hyperspectral sensors using several detection algorithms. Limited antitank mine detection performance estimates for the multispectral COBRA sensor are available in Stetson et al. [16].

Limitations. The sensor concepts described here, like the other passive sensors described above, are limited by uncontrollable variation in solar illumination. Surface mine signatures are also strongly sensitive to the sun angle, which causes shadows and heating on specific parts of the mine. Additional sensor-specific issues arise. Passive polarimetric signatures tend to be weak for mines with rough surfaces. For mines with smooth surfaces, the polarimetric signature is strongest when viewed at low elevation angles. Unfortunately, at those angles, the mines can also be obscured by vegetation. Hyperspectral sensors also have limits. In principle, the spectral signature of mines can be measured and subsequently used to improve detection algorithms, but the unpredictable effects of rust, dirt, and material aging make it difficult to do so. Fielded hyperspectral detection algorithms often comprise simple anomaly detectors.

Potential for Improvement. Greater use of hyperspectral and polarimetric methods will permit more information per pixel, which aids detection. More extensive tests should be conducted on antipersonnel mines to determine the true performance of these sensors. In such work, improved spatial resolution will be required. Finally improvements in image processing techniques are likely to offer significant gains.

Active Sensing for Surface Mines

Physical Basis. Only active sensors of nonthermal phenomena are of interest because actively provoking a thermal signature from a significant distance requires impractical amounts of power. The relevant physical phenomena for this sensor concept have been described above. The use of active sensors is appealing for polarimetric sensors in which a fixed polarization can be transmitted. The basis for an active polarimetric sensor is quite different from the passive polarimetric sensors noted above, in which low elevation angles are preferred to detect the polarized signature of the mine. Active sensors tend to operate at near-nadir viewing angles, where a smooth mine surface will not depolarize the (polarized) illumination, while scattering from randomly oriented foliage will be depolarized.

Development Status. Active sensors have been extensively investigated by a number of U.S. programs, including the REMIDS and ASTAMIDS studies. The Army is currently developing the LAMD-Laser system, in which a polarized laser illuminator will be used to detect co- and cross-polarized returns from surface antitank mines. Current plans call for fusion of the active sensor and a passive MWIR imager. Other sensors have been investigated. Three active sensors operating in the NIR and short-wave infrared (SWIR) bands have been demonstrated by de Jong et al. [28] in the Netherlands. Those experimental sensors were used in controlled, small-scale outdoor tests on a smooth sand background. An active hyperspectral imaging system was demonstrated by Johnson et al. [29], who imaged a number of artificial materials in vegetation. Tripwire detection is a closely related field of interest. Relevant work is described by Allik et al. [30] for SWIR sensors and by Babey et al. [31] for ultraviolet, VNIR, and SWIR.

Current Performance. Results were presented in de Jong, Winkel, and Roos [28] for a test site having 25 surface-laid mines and clutter objects on a smooth sand background. Although most of the objects show high contrast, no performance data are provided. Summary minefield performance data for the REMIDS sensor are given in Stetson et al. [16]. No performance data are yet available for the LAMD-Laser system, although at the time of this writing preliminary data had been acquired from several tests sites. Sensor enhancements and algorithm development are under way.

Limitations. A number of relevant issues were noted in the previous Limitations subsection. The need to operate at near-nadir viewing angles for active polarimetric sensors was described above.

Potential for Improvement. As noted, there is little performance data available on antipersonnel mines for active sensors, but exploratory tests have been encouraging. Future work should focus on a quantitative assessment of this sensor concept.

R&D PROGRAM RECOMMENDATIONS

EO sensors are among the most attractive technologies for achieving wide-area antipersonnel mine detection. Although they have been investigated at some length for antitank mines (and minefields), they have not been explored significantly for antipersonnel mines. To address this deficiency, any R&D program should include the following activities:

- creation of an antipersonnel mine test range with a statistically significant number of mines
- collection of baseline data sets on that test range
- development of suitable processing algorithms leading to performance statistics
- closer collaboration with European colleagues working in this area.

Some specific research goals are as follows:

Passive Thermal Detection of Buried and Surface-Laid Mines

A better understanding of the processes that produce thermal mine signatures should be initiated for both buried and surface mines. A combination of theoretical and experimental work is required. The environmental parameters required to predict thermal IR performance should be determined. The goal of the work should be a model using environmental parameters as inputs and capable of predicting the best times to deploy thermal IR sensors.

Active Thermal Detection of Buried Mines

Further investigation of the HPM approach is warranted, beginning with an investigation of the nonuniform illumination problem and definition of an operational sensor concept.

Active and Passive Hyperspectral Detection of Mines

Buried mine detection should be investigated first. A better understanding of the phenomena that produce hyperspectral signatures for disturbed soil and vegetation stress should be undertaken. Signatures should be acquired both for recently buried mines and for mines that have been allowed to "weather in." Both bare soil and vegetated surfaces should be examined. A hyperspectral sensor with high spatial and spectral resolution should be developed and used in the testing. The sensor should also be used to image both buried and surface mines, and a comparison of hyperspectral and polarimetric detection (see next paragraph) should be undertaken.

Active and Passive Polarimetric Detection of Surface Mines

Past experience with active polarimetric sensors (e.g., REMIDS) for surface antitank minefields has demonstrated encouraging performance, and further development of this concept (e.g., LAMD-Laser) is under way. Tests of new sensors should also be performed for antipersonnel mines using commensurately smaller spatial resolution. A passive, imaging polarimetric sensor should be fielded and tested. Data on a large set of antipersonnel mines should be acquired. The data acquisition effort should be supported by a parallel effort in detection algorithm development.

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