Advanced Land Mine Detection Using a Synthesis of Conventional Technologies

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The humanitarian need for new, technologically advanced yet cost-effective approaches to demining has recently become critical. First, the proliferation of mines has increased to the extent that not only are there more than 100 million mines buried throughout the world, but new mines are being placed faster than they can be cleared. And second, newer types of mines with inexpensive plastic and non-ferrous metal casings—which are difficult to detect with conventional methods—are becoming more prevalent.

Developing the next generation of demining technology requires using multiple sensors and signal processing algorithms which take into account the way in which the sensor data is gathered rather than treating the data as generically-derived information. We at Northeastern University are leading a team to develop and optimize land mine detection based on ground-penetrating radar (GPR), infrared thermography (IRT), electromagnetic induction (EI), and high frequency acoustic (HFA) sensors. We are implementing sophisticated, physics-based mathematical models to describe the interaction of EM or acoustic waves with mines buried in realistic (electromagnetically lossy, inhomogeneous) soil and as a result are developing "smart" signal processing algorithms to identify and classify mines. These mathematical models are derived from actual soil and land mine measurements, and include detection statistics of the sensors. In addition, we are building prototype land mine detection systems using currently available industrial hardware configured in novel ways based on the physical models under development. This approach allows us to utilize cheap, off-the-shelf components and "smart" algorithms with the hope of providing developing countries with reliable and cost-effective sensor systems. Finally, we are working to integrate these components into a set of scenario-tunable systems for person-portable, vehicle-mounted, and/or airborne use that will be effective for demining operations in both hostile and peaceful areas.

To achieve these goals requires a research program based on a first-principles understanding of the technical challenges posed by the demining problem and the development of an integrated framework for addressing these issues. At its root, the demining problem is particularly challenging because it is an *inverse* problem. That is, one can often obtain information regarding the presence of mines *only* through indirect measurements using electromagnetic, chemical or thermal sensors. Most sensing systems operate by transmitting energy into the earth and measuring the scattered fields arising from the interaction of the energy with sub-surface structures. All mine-related information to be extracted from the data is encoded by the complex scattering processes underlying these non-invasive detection methods.

Non-ferrous mines are undetectable with magnetometry, while quick mobile deployment precludes particle beam and spectrometry methods. Shallow wave penetration in soil limits millimeter and visible frequency techniques, while resolution limitations create difficulties for seismic and gravity sensing. Although olfactory, chemical, and biological sensing may offer advantages for detecting older mines (and hence be useful for humanitarian purposes), they have limited sensitivity, especially in battlefield situations where pervasive explosive residues may be widely scattered across the ground. Newer mines do not give off significant chemical vapors and there is no direct means of continuously sampling soil.

By concentrating our efforts on EI, GPR, IRT, and HFA sensors, we feel that we have the best opportunity for making significant advances in demining. These technologies have been available for many years, and have individually met with limited success. Most importantly, all four technologies are easily integrated since they possess similar modalities, involve similar wave propagation, can be addressed with unified mathematical models, and can be mounted on a variety of demining platforms. We are performing experiments to determine the optimal platforms, sensors, and frequency ranges for specific demining situations and plan to exploit the capability of multiple sensors and physically-based signal processing algorithms to generate substantial improvements over currently available land mine detection schemes.

Ultrawideband Array-Based Ground-Penetrating Radar

As with standard radar, GPR is useful for the remote sensing of submerged targets. It is an important tool for determining the locations of unexploded ordnance, land mines, underground installations, and hidden arms caches, but also offers many dual-use applications, including precisely identifying the positions of buried waste drums (for environmental clean-up), finding pipes or cables (of interest to utilities), and identifying cavities or obstacles (for construction applications). Ground penetrating radar has been available for many years, and has been fairly successful at the remote identification of buried objects. However, by making use of short pulse and shaped pulse signals, several important advantages become apparent. First, for wet, lossy soils, the wave penetration depth is severely limited for high frequency signals, while the detector resolution is limited at low frequencies; short pulse signals can be tailored to optimize the trade-off between penetration and resolution. Second, since most of the targets are in the nearfield of the radar source, the signal phase effects are unusually important. By mixing the phases of a wide bandwidth of frequencies appropriately, the signals scattered by the target can be more sharply analyzed, and the targets more accurately identified.

Soil is inhomogeneous and dispersive, with dielectric and electrical conductivity parameters depending on the soil composition, density, and excitation frequency. One research effort at Northeastern University uses measured soil data to form a simple clutter model appropriate for both time- and frequency-domain computational wave propagation simulations. In addition, we will include the effects of dielectric constant and conductivity variations as well as rock inclusions as perturbations of the propagation medium. Instead of having to guess soil characteristics or use a look-up table, this model will provide high-accuracy predictions of the penetration depth, resolving capability, and sensitivity to noise and clutter of the EM signals.

It is only through use of the entire RF frequency band and the largest possible aperture that sufficient sensing information becomes available for sophisticated inversion processing. While monostatic data from various locations can be combined for rudimentary imaging, collecting the scattered response with multiple receivers simultaneously provides the extra dimension of information necessary to detect low contrast mine targets. We are developing strategies for optimizing element positioning in one- and two-dimensional arrays, considering synthetic aperture radar (SAR) antenna optimization, and testing trade-offs between array size and platform geometry for synthesizing the best practical sensing aperture.

For the ultra-wideband radar systems we will be developing, it is essential to make use of antenna elements which are compact, efficient, inexpensive, and can faithfully radiate all of the frequency components in the generated radar signal. Geo-Centers, Inc., an industrial partner of Northeastern University, has developed a novel wideband antenna based on a transverse electromagnetic horn with rhombic taper, folded back into itself and terminated with a 50 ohm resistive load used for both transmitting and receiving. The measured performance of this transverse electromagnetic rhombus (TEMR) indicates a very uniform radiation pattern in the plane of curling flare, perpendicular to the metal plates. It is also a wide-band antenna; throughout the 200 MHz to 2.0 GHz range, the radiated signal faithfully duplicates the input signal shape *for all angles*. Thus, the TEMR appears to be close to an optimum antenna element for a time-domain radar array. This wideband antenna has been incorporated into a time domain array as part of a vehicle-mounted GPR countermine system. The detection results for this system have been very encouraging, with 100% of all metal mines and over 90% of plastic mines detected in realistic simulations.

Microwave Enhanced Infrared Thermography

In addition to using individual microwave and infrared sensing systems, we propose a hybrid sensor in which a high-power microwave transmitter is combined with an infrared camera. The transmitter introduces energy into the ground which is absorbed at a different rates by buried objects and the surrounding soil. The resulting differential heating is sensed by the infrared camera thereby leading to an image of the underground object.

While careful modeling will be required to evaluate performance and optimize the transmitting antenna design, the basic soundness of the approach has been demonstrated with simulated differential sunlight heating. We are examining the selection of a microwave wavelength to penetrate to the desired mine depth making use of the dielectric contrast of the mine as well the contrast in its thermal parameters. Microwave energy can be focused and directed into the ground at the pseudo-Brewster angle to minimize reflection and thus maximize coupling. For the common variations in soil characteristics, an elliptical reflector-type antenna could be positioned so that its major axis aligns with the Brewster angle far in front of a detector. The converging rays from all parts of the elliptical reflector will arrive at the target focal point with a range of angles. Finally, by taking IR images before and after energy is delivered, difference images can be constructed which will reduce the masking.

Acoustic Phenomena

Although the acoustic mismatch between particulate soils and solid mines makes acoustic sensing a promising area of research for mine detection, previous studies have demonstrated the difficulty of coupling sufficient acoustic energy from air into the ground. Contact sensors, on the other hand, are slow and awkward for use by moving troops, and dangerous in applications where pressure must be minimized.

One alternative is laser-induced acoustic-wave generation. CO_2 laser pulses are strongly absorbed in the surface of most solids. Modulating the laser power at acoustic frequencies produces audible and trans-audible sound vibrations. The dominant frequencies have been identified with dimensional resonances in a 300 cm^3 irregular sample. Applied to a mine detection system, the laser could be raster-scanned across the area under investigation with detection through a remote ground contact or rolling sensor array. Acoustic resonance when excitation is near a mine could be correlated with the mine position by knowing the laser excitation position.

Acoustic array signal processing will benefit from the concurrent work in electromagnetic signal processing. Multistatic processing of acoustic signals will closely parallel the work on multistatic EI and GPR. Algorithms for multistatic GPR and EI will be tested with simulated or experimental HFA data to measure the enhanced probability of acoustic detection from array processing.

Summary

Although there undoubtedly exist more exotic sensors which could be used for detecting land mines, we expect that clever use of mature technologies will ultimately prove to be efficient, cost effective, reliable, and with a shorter development horizon since we will utilize commercial, off-the-shelf components which already exist. The novel aspects of Northeastern University's approach are: (1) to combine multiple sensors synergistically, yielding more information than would be available to any single sensor technology operating alone, and (2) to use "smart" signal-processing algorithms derived from physics-based models which take into account the actual sensor parameters as well as material and electrical characteristics of the soil and land mines. By processing data in an intelligent manner, rather than simply treating it as a generic bit stream, we hope to utilize information that would otherwise be discarded, and which will make mine detection much more successful.