Metal Detection and Classification Technologies

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From the detection of buried treasure to the detection of landmines and unexploded ordnance, the history of metal detectors is long and varied. This article reviews the basic technology for detecting metal objects using electromagnetic induction techniques. Working with the U.S. Army Night Vision and Electronic Sensors Directorate and other government agencies, APL has developed a number of advanced metal detection and classification techniques. Several prototype sensor systems have demonstrated capabilities to detect, discriminate from clutter, and classify high- and medium-content metal landmines in addition to some plastic landmines. The prototype sensors have also shown potential for detecting mines with very low metal content because such mines create a void in some types of electrically lossy soils. Compared to conventional electromagnetic induction metal detectors, the APL prototype sensor's discrimination feature results in a lower false alarm rate from metal clutter.

INTRODUCTION

The first known use of a metal detector dates back about 200 years ago in China[1] when a doorway made of an iron metal "attractor" (possibly magnetite) was constructed to protect the Chinese emperor from people carrying metal objects. Alexander Graham Bell may be remembered as the first person to use an electrical metal detector to find a bullet in President James Garfield after an assassination attempt in 1881. The first documented treasure-hunting metal detector appeared around 1930. Rapid advances in modern electronic metal detectors were developed during World War II as a means to detect buried metal landmines. In the 1940s and 1950s, buried conductive object classification was mainly confined to geophysical exploration for buried minerals. In the 1970s, the electronics revolution in integrated circuits and the treasure-hunting hobbyist metal detection market spurred the development of a variety of sophisticated, handheld, low-power, and low-cost metal detection technologies. The 1980s saw the development of the necessary theoretical underpinnings to further the metal discrimination concept. Progress over the last 10 years in microelectronics, microcomputers, signal processing, and electromagnetic modeling has translated into more improvements. Today's hobbyist metal detectors use advanced signal processing microcomputers to analyze buried target signatures to discriminate clutter objects from coins and jewelry. The landmine and unexploded ordnance (UXO) research community has also taken advantage of this progress to develop sophisticated detection and discrimination technologies.

The scope of the metal detection and classification problem can be quantified easily.[2] The number of landmine and UXO civilan casualties is estimated by the United Nations to be over 20,000 per year in 70 countries worldwide. An estimated 100 million mines and hundreds of thousands of square kilometers of land contaminated by UXO exist worldwide. Remediation of these dangerous legacies of long-forgotten wars is a major concern. In addition, the recent focus on national security has renewed interest in improved metal detection and discrimination technologies. Security screening for concealed metal weapons has become commonplace in public buildings and transportation centers.

Current state-of-the-art electromagnetic induction (EMI) metal detectors can detect small metal objects at shallow depths and large metal objects at greater depths under a wide range of environmental and soil conditions. However, nonlethal metal (clutter) objects commonly found in the environment are a major issue. Because these clutter objects represent false targets, they create a false alarm (potential landmine/UXO or metal weapon) when detected by a conventional metal detector. Ideally, the detected metal targets should be classified as to their threat potential: landmine/UXO, weapon, or clutter. This article describes several current research projects at APL that focus on solving this metal target detection and classification problem.

TECHNOLOGY BASICS

Figure 1 shows a simplified diagram of the basic pulsed-EMI technique. A current loop transmitter is placed near the metal object, and a steady current flows in the transmitter for a sufficiently long time to allow turn-on transients in the object to dissipate. The loop current is then turned off. According to Faraday's law, the collapsing magnetic field induces an electromotive force in the metal object. This force causes eddy currents to flow in the metal. Because there is no energy to sustain the eddy currents, they begin to decrease with a characteristic decay time that depends on the size, shape, and electrical and magnetic properties of the metal. The decay currents generate a secondary magnetic field, and the time rate-of-change of the field is detected by a receiver coil located at the sensor.

If a conductive object is shown to have a unique time-decay response, a signature library of conductive objects can be developed. When a concealed metal object is encountered, its time-decay signature can be compared to those in the library and, if a match is found, the object can potentially be classified. Classification allows discrimination between potential threat and nonthreat objects.

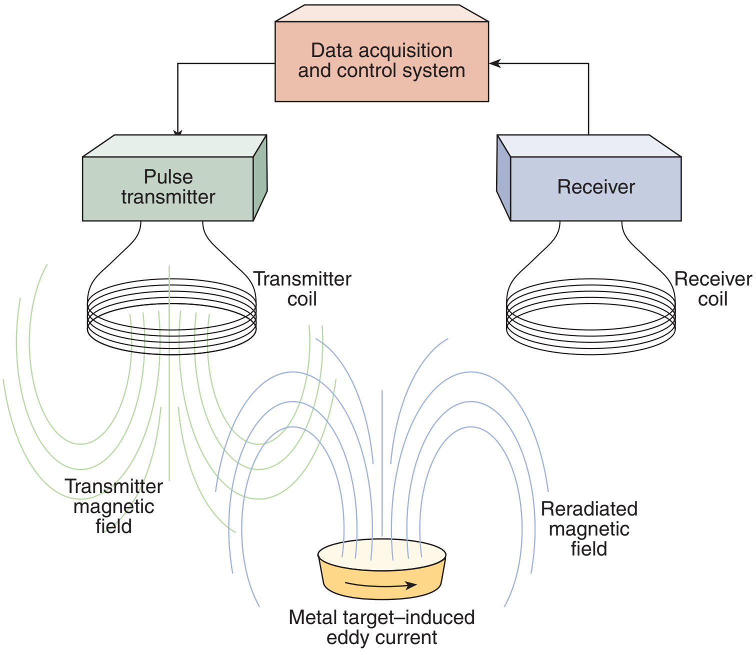

Figure 1. Basic pulse induction metal detection scheme.

DETECTION AND CLASSIFICATION

Landmines

Stealth is a buried landmine's major defense against neutralization. Since the primary tool to find a landmine has historically been the metal detector, landmine manufacturers have developed low metal content (LMC) plastic-encased landmines to minimize the chance of detection. These landmines have as little as 0.5 g of metal content. Great effort has been expended by metal detector manufacturers to develop sensitive metal detectors to identify these small metal objects at depths of tens of centimeters in all soil types. Currently, the best hobbyist and military metal detectors can find, with high confidence, these LMC landmines at a distance of about 20 cm. However, the increased metal detection sensitivity subjects the de-miner to increased false alarms owing to small metal clutter not previously detectable. It has been estimated that for every real landmine detected there are as many as 100 to 1000 metal clutter objects detected.[3] Obviously, it is desirable to be able to discriminate the metal clutter from the real landmine.

Since 1997, APL has been developing a high time resolution, wideband time-domain metal detection sensor system called the Electromagnetic Target Discriminator (ETD).[4,5] The prototype ETD

(Fig. 2) has demonstrated, in laboratory and blind testing, the capabilities to detect and discriminate high- and medium-content metal landmines from metal clutter of similar metal content. In addition, the system has shown the capability to detect, and in some cases classify, some LMC plastic-encased landmines using time-decay and spatial features of the landmine signature.

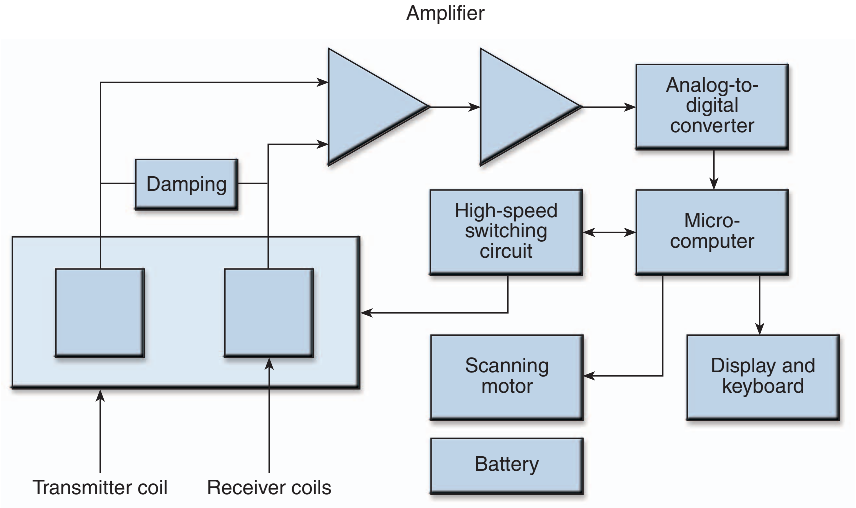

Figure 2. Simplified block diagram of the metal detection sensor, a component of the Electromagnetic Target Discriminator (ETD).

The prototype ETD sensor was constructed using commercial off-the-shelf technology and was designed to demonstrate advanced detection and discrimination capabilities. It differs from conventional metal detectors in several aspects. First, the sensor's high-speed data collection system accurately measures the time-decay signature of the metal object. Second, its bandwidth is about 10 times that of other metal detectors, thus allowing the sensor to detect small, fast-decaying metal objects not normally detectable with a conventional metal detector. And third, the sensor uses a differential or gradiometer coil antenna design that has several advantages over most conventional metal detector coil antenna designs: automatic ground balance, mineralized soil effect rejection, void detection, far-field noise minimization, and cancellation of transmitter coil decay currents.

Mine simulants (called "inserts") representative of a wide range of metal parts commonly found in LMC anti-personnel and anti-tank mines were developed by the Army for convenient testing of metal detectors. The inserts contain 0.5 to 3.3 g of various combinations of steel, copper, and aluminum. Figure 3 is a log-log plot showing the distinct in-air time-decay responses of the mine simulants centered over the sensor's antenna. These differences form the basis of landmine classification.

A spatial scanning version of the ETD sensor[6] was developed to take time-decay signature measurements over a buried target as a function of horizontal position. A typical LMC anti-tank landmine is a plastic cylinder about 23 cm in diameter and about 10 cm tall. The flat cylinder is filled with explosives and has a small metal firing pin in the center. When buried, the anti-tank landmine displaces a large amount of soil and creates an electromagnetic void in the soil if the soil is electrically lossy. Electrically lossy soil is typically composed of very fine particles of mineralized iron that have a fast decay signature not measurable by conventional low-bandwidth metal detectors. Figure 4a shows a spatial/time signature from a LMC anti-tank landmine buried about 3 cm below the surface of clay/sand loam soil. The red in the center of the figure is the metal signature (positive voltage), while the blue is the fast time-decay signature of the void created by the displaced soil. Figure 4b more clearly shows the void phenomenon using a LMC anti-tank landmine simulant with no metal parts. The spatial signature has a significant void signal (noted by the strong negative voltage on the plot) near the center and no metal signature as in Fig. 4a. These time-domain measurements are the first to show definitively simultaneous metal and void signatures for buried LMC landmines. The existence of coincident metal and void signatures is a positive detection and classification of a LMC landmine.

A prototype target classification algorithm (TCA) based on the statistical properties of the time-decay signatures and spatial features from the scanning ETD sensor is under development at APL. The TCA first

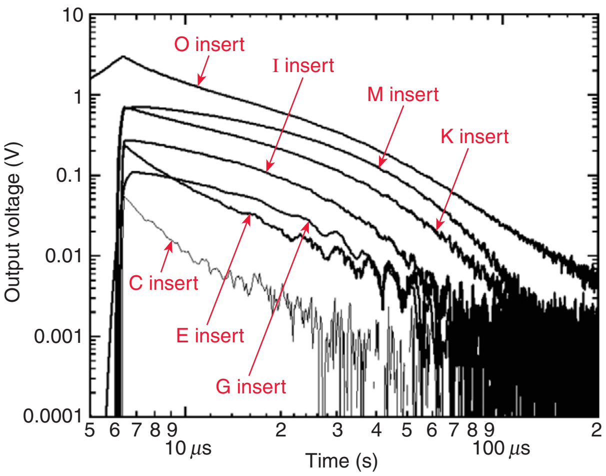

Figure 3. Time-decay signatures of select low metal content anti-personnel and anti-tank landmine simulants ("inserts") containing 0.5 to 3.3 g of various combinations of steel, copper, and aluminum.

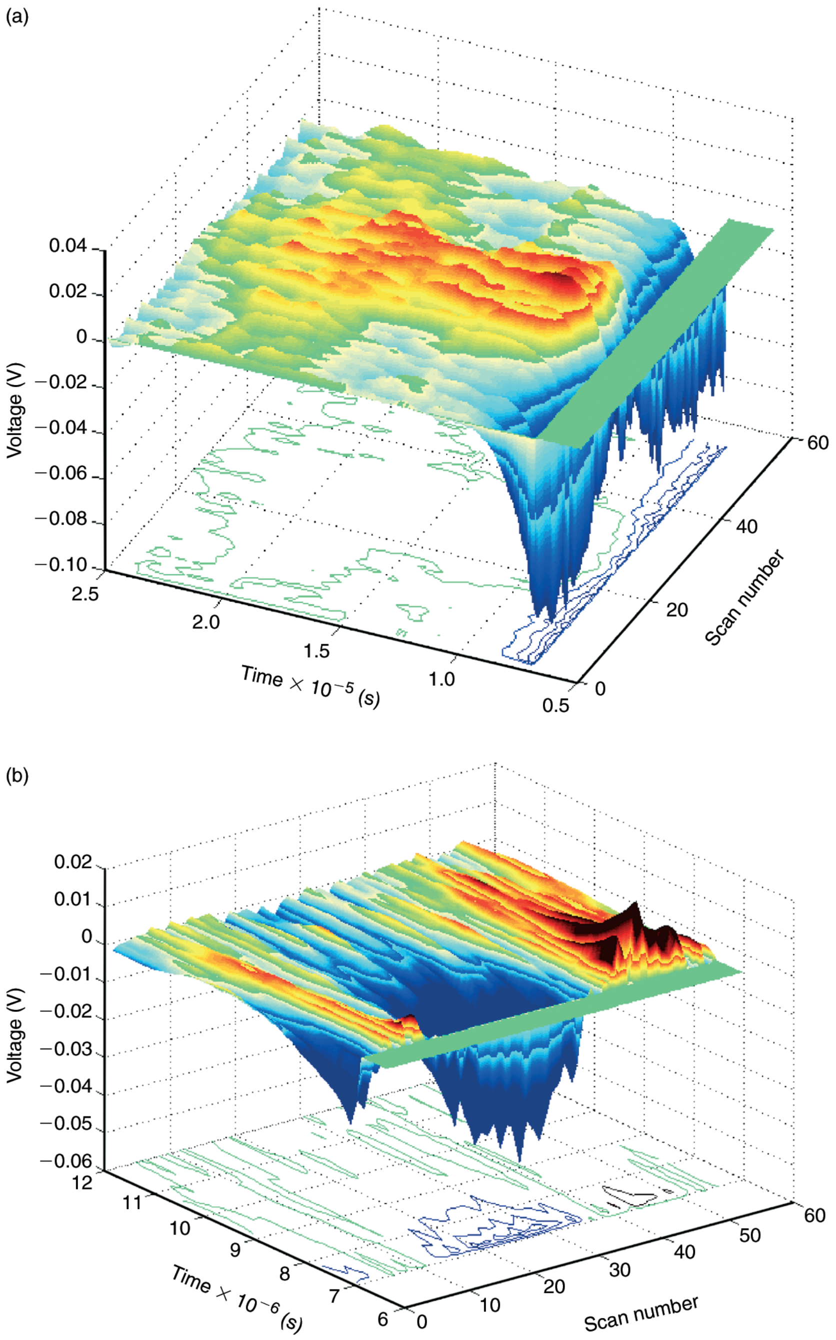

Figure 4. Time-decay signatures from a spatial scanning ETD sensor over a low metal content anti-tank landmine simulant (a) with and (b) without metal parts. Red represents the metal signature (positive voltage) and blue the fast time-decay signature of the void created by the displaced soil.

does a statistical amplitude sort. Data are next sorted by log-linear time-constant estimation. The estimated time constant is then used to quickly select potential signature templates from a library of known threat targets for target matching. Various time-decay curve-matching calculations are subsequently made as to the goodness of fit to the various library templates. In addition, other features, such as amplitude and time-decay symmetry and the presence of a void signal, are extracted from the data and compared to the library features for targets that closely match the unknown target. To date, medium and high signal-to-noise ratio (SNR) targets have had a nearly 100% probability of detection with very low false alarm rates. Low SNR time-decay signatures make classification more difficult. The algorithm must have sufficient SNR to be able to extract target features for accurate classification.

Unexploded Ordnance

The detection of metal objects in a UXO environment is typically not difficult when compared to the detection of landmines, but discrimination is more problematic because of the large range of sizes, shapes, material composition, and object depths. UXO ranges in size from 20-mm shells to 1000-lb bombs. They are found in a range of depths from the surface to over 4 m. Some UXO environments contain large amounts of steel, aluminum, and brass. Compared to landmines, which have a preferred buried orientation, UXO can be oriented in any direction, thus complicating target discrimination via a unique time-decay signature.

For a time-domain EMI sensor system, a metal target can be modeled by defining a magnetic polarizability tensor that contains the target's primary magnetic decay response modes[6]:

$$\vec{M} = \begin{pmatrix} M_x(t) & 0 & 0 \\ 0 & M_y(t) & 0 \\ 0 & 0 & M_z(t) \end{pmatrix}, \quad (1)$$

where the diagonal components of the tensor are the time responses of the target to excitations in an orthogonal reference frame centered on the target. In an orthogonal xyz coordinate system, $M_x(t)$, $M_y(t)$, and $M_z(t)$ are the target's decay response to a magnetic field excitation in the x, y, and z direction, respectively. For an axially symmetric or body-of-revolution target, $M_x(t)$ and $M_y(t)$ are equal.

Most EMI sensors designed for UXO detection and discrimination do not take advantage of the available information that is inherent in the metal target's electromagnetic response to an external magnetic field excitation. Rather, these sensors tend to measure only a single dimension of a target's response or, in the case of a spatially scanned metal target, try to infer a multidimensional response. Some experimental EMI sensors that do attempt to generate a three-dimensional (3D) magnetic field and measure a target's 3D response do so with magnetic field antennas that have complex spatial magnetic field distributions.

In 2002, APL started developing a novel 3D steerable magnetic field (3DSMF) sensor[7] that orients the excitation magnetic field into the primary axis of the target. Once the primary axis is found, the antenna's magnetic field is rotated into the secondary axis of symmetric objects. For symmetric objects, classification is fairly straightforward using conventional classification algorithms based on a library of magnetic polarizability tensors. For nonsymmetric objects, the 3DSMF sensor measures the object's response in 4 π steradians. The classification algorithm then tries to match the object's 3D response to a target library of nonsymmetric objects.

To appreciate the new technology and to better understand its operation, we briefly review some basic physics. We note that, for an infinite conducting sheet current in free space, the magnetic field in the direction perpendicular to the sheet current is given by

$$B = \mu_0 \nu / 2 \ , \qquad (2)$$

where ν is the current density in the sheet. Expressed another way, the sheet current is a horizontal magnetic field (HMF) generator or antenna. The important feature of Eq. 2 is that the magnetic field is constant with z, the distance from the plane of the antenna. To take advantage of this feature, we create a practical approximation of an infinite sheet current by placing closely spaced current-carrying wires in a plane. The result is a magnetic field with a relatively uniform horizontal shape and a slow-intensity falloff, with distance from the plane of the antenna relative to a conventional dipole loop. The return current path, which reduces the magnetic field strength, is placed far from the active area of the sensor to minimize its effect.

To conceptualize the 3DSMF sensor, we need only imagine two single-axis HMF antennas co-located at right angles to each other. This arrangement forms a 2D horizontal field–generating antenna. The third dimension to the magnetic field is created by adding a horizontal loop antenna to the two HMF antennas as shown in Fig. 5. Thus, we can create a magnetic field vector in 3D space by varying the current in each antenna element employing superposition of the fields of each antenna. The target's response to the excitation field is measured by suitably placed magnetic field sensors.

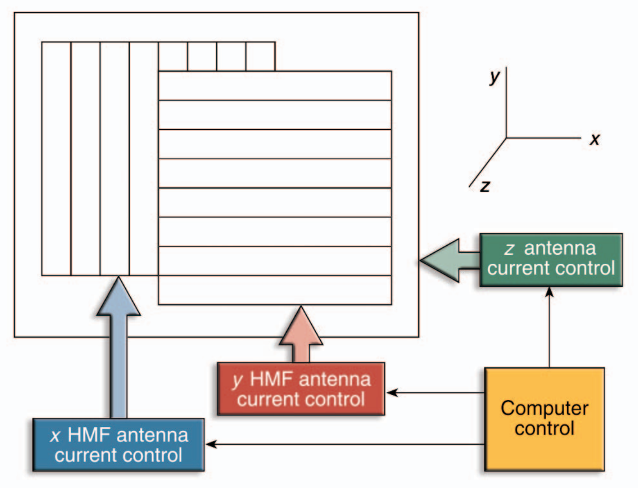

Figure 5. Simplified block diagram of a 3D steerable magnetic field (3DSMF) sensor system (HMF = horizontal magnetic field).

In addition to UXO classification, the 3DSMF sensor has potential for enabling metal classification in personnel screening devices used for weapon detection based on metal detection technology. The sensor is also likely to reduce the false alarm rate of detected metal.

Wide-Area Metal Detection

With the increased security needs of national defense comes a need for a metal detection system to screen large numbers of people attending public events for metal weapons such as guns, knives, and shrapnel-laden explosives. Conventional metal detectors require people to walk through a small metal detection portal one at a time. This creates a "choke" point, and long lines typically form when the number of people exceeds the capacity of the metal detection screening process. The Wide-Area Metal Detector (WAMD) sensor system[8] enables metal detection prescreening and can be used to locate people in a crowd that may require further investigation. This prescreening could greatly reduce the need for everyone to be "scanned" for potential weapons with a high-sensitivity portal-type or handheld metal detector.

The WAMD sensor system is currently in development at APL and is based on a large version of the HMF metal detection antenna concept described above. The HMF antenna is combined with a video surveillance system to monitor a large area for people who may be carrying metal objects. Those with concealed metal objects that exceed a threshold will trigger the WAMD alarm. A video surveillance system will then be cued to the area where the metal was detected, allowing the video system operator to direct a security person in the surveillance area to locate and investigate further the person who set the alarm off. Figure 6 is an artist's conception of the WAMD.

Figure 6. Wide-Area Metal Detector (WAMD) sensor system concept.

SUMMARY

This article has demonstrated a few areas where APL has improved upon and extended the technology of the humble metal detector to solve age-old problems of metal detection and classification. In addition, we have found new and innovative applications to solve today's national security threats.

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