Innovating on Top of I&M Fundamentals for Safer Humanitarian Demining

Davorin Ambruš, Darko Vasić, and Vedran Bilas

In this paper, we explain how the requirements for rigorous, well-defined standard operating procedures, and simple, robust, inexpensive and easy-to-use detection equipment affect key aspects of instrumentation and measurement (I&M) systems applied to landmine detection in humanitarian demining. We also show how fundamental knowledge in physics and I&M, as well as industry's practical know-how (accumulated over the past decades), can be combined with new technological advancements to build devices with improved abilities to detect, characterize, classify and locate buried hazardous objects. We use a handheld metal detector as an illustrative showcase of a relatively simple, low-cost and well-established I&M technology. The challenge is to upgrade such a device with object discrimination capabilities by bringing scientific and technological innovations at three different levels: signal level, feature extraction level and feature interpretation level.

Background on Demining Technology

Buried explosive devices, such as antipersonnel landmines and unexploded ordnance (UXO), present a deadly legacy of armed conflicts and a global humanitarian problem [1]. Once left in the ground, such devices can remain operational years after cessation of conflicts, inflicting heavy injuries or deaths when triggered by a victim. Landmines and UXOs contaminate some 60 countries in different environmental settings such as deserts, jungles or urban areas, where more than 60 million people are affected either directly, or indirectly through restricted access to food, water or other basic human needs. In spite of significant efforts engaged over the last two decades to clear the world from buried explosive hazards, recent statistics reveal that mine accidents are on the rise again, mostly due to recent conflicts in Syria, Iraq and Afghanistan [1]. Improvised explosive devices (IEDs), planted to act as industrial landmines, are another big threat that is becoming more widespread, requiring adequate response from the mine action community.

Humanitarian demining provides a set of activities aiming to completely remove all of the explosive hazards from a given area and make the land safe for the returning population. Unlike military demining, which is all about speed and reducing the risk for a reasonably safe passage of troops, in humanitarian demining the focus is always on safety and thoroughness so that ideally, no dangerous objects are left in the ground [2]. Consequently, mine clearance becomes an extremely labor-intensive and time-consuming process. Since the demining is normally performed by individuals who cannot be considered highly-trained technical experts (e.g., ex-soldiers), and due to the fact that humanitarian organizations usually operate on tight budgets, demining work is based on two main pillars:

- rigorous, well-defined standard operating procedures, and
- simple, robust, inexpensive and easy-to-use detection equipment.

I&M Fundamentals and Demining Industry's Know-How

Metal Detection

The oldest and still the most widely used method to detect buried landmines is based on the application of electromagnetic induction (EMI) to detect their metal content such as igniting pins, detonator cases, or other metal parts of triggering mechanisms [2]. EMI devices generate time-varying magnetic fields and detect weak scattered fields emanating from eddy currents and bound magnetization currents induced within metallic objects. They typically operate in a low-frequency (few kHz to tens of kHz) quasi-magnetostatic regime.

Since modern plastic encased mines feature extremely low amounts of metal (making them cheaper to produce and harder to detect), metal detectors (MDs) have evolved accordingly in terms of their sensitivity. State-of-the-art MDs which are nowadays used in demining operations are typically able to detect such low-metal mines up to reasonable depths (depending on operating conditions). However, their inability to discriminate between metal parts of hazardous devices and innocuous metallic clutter, such as battlefield debris and shrapnel, leads to huge amount of false alarms. In practice,

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demining teams often encounter between 100 and 1,000 false alarms per mine [2]. Since the standard operating procedures most often require that each piece of metal is removed from the ground (no metal = no mine policy), this means that hundreds of innocuous items must be prodded and excavated, which increases a deminer's fatigue and may eventually lead to loss of concentration, missed mines or casualties.

Ground Penetrating Radar (GPR)

Motivated by the need to reduce the false alarm rates in humanitarian demining, researchers have investigated other sensing modalities to improve clutter rejection. A general idea behind most of these efforts was to identify a viable sensing modality that could ultimately lead to development of a portable, real-time landmine confirmation sensor. Such a sensor would not be used as a standalone device, since the probability of detection close to that of an MD is extremely difficult to achieve, but rather as a tool to confirm or reject the alarms coming from a metal detector. The idea of applying GPR to landmine detection came from the fact that it can be observed as a sensing modality complementary to MD. Whereas MDs detect metallic content of buried landmines, GPR could be used for detection of their plastic casings (and potentially explosive charges). Simultaneous detection of metal parts and the surrounding plastics could then be used as a more reliable indication of a buried landmine.

GPR operates by emitting electromagnetic waves (between few hundred MHz and several GHz) into the ground and analyzing the return signals generated by reflections of the waves at the boundaries of materials with different indexes of refraction. Weak return signals are picked up by receiving antenna(s) and processed to create either an image of an underground object or an audible detection signal. In general, GPRs require very sensitive receivers and sophisticated signal processing to extract the target signal from background interference and signals corresponding to clutter objects such as rocks, plant roots, or pockets of water [2], [3].

Although dual-sensor detectors, combining MDs and GPRs into a single device, have been developed and used in the field for some time, GPRs are still considered a rather expensive technology, since the price of a typical handheld GPR device is an order of magnitude higher than that of a state-of-the-art MD. Consequently, dual-sensors detectors are nowadays predominantly used by the military, so the engineering challenge is to devise affordable dual-sensor detectors for the humanitarian demining market. A potential solution might be to take advantage of relatively inexpensive electronic components used in consumer products in a rapidly developing wireless communications market [3].

Lessons Learned

Other sensing technologies such as acoustic/seismic sensing, infrared cameras, nuclear quadrupole resonance for bulk explosive detection, different chemical/biological methods for explosive vapor detection, etc. have also been investigated in a context of close-in landmine detection [2]. Although valuable in a scientific sense, these research efforts did not result in detection tools that could be reliably used in practical demining scenarios. Such experimental devices were either not sensitive enough, too bulky, too power-hungry, too expensive, difficult-to-use, or just incapable of operating in adverse conditions of a minefield.

Motivated by the low take-up of new technologies, there has been a notable decline in funding of research activities for humanitarian demining, starting from the mid-2000s to present days. Consequently, the demining industry has turned to a concept of incremental improvements to established detection technologies and methods, such as MDs, instead of relying on development of completely new technologies [2], [8].

Improving the Abilities of Conventional Metal Detectors

As already pointed out, MDs are relatively simple and inexpensive devices, and there is generally a good understanding of their benefits and drawbacks, both in the scientific and demining community. Compared to first models designed back in the times of World War II, modern state-of-the-art MDs are more sensitive, low-power, more convenient to use, as well as capable of compensating the electromagnetic effects of mineralized soils (albeit with some loss of sensitivity). In general, the MD industry is still considered rather conservative, so up until very recently it was not so uncommon to find that fully analog models of MDs are still being produced. On the other hand, the industry has accumulated a lot of practical/empirical knowledge through field exploitation of these devices over the past decades. Such know-how is priceless for applications such as humanitarian demining. Some of the well-kept secrets of the industry relate to simple and proven electronic circuit designs, mechanical/thermal designs of coil assemblies that deliver greater stability during sweeping motion, coil shielding to reduce capacitive effects without disturbing the basic sensitivity of a device, etc. Building new I&M concepts on top of existing knowledge seems therefore like a promising approach aimed to provide the incremental improvements the demining industry is looking for.

Signal Level

Observing conventional MDs at the level of raw signals, we can identify three specific areas where improvements can be made both in a context of basic metal detection, as well as metal characterization or discrimination:

- Excitation signal chain,
- Receiver signal chain,
- Search head geometry.

When it comes to the type of excitation, there are currently two kinds of MDs: the ones using continuous wave (CW) signals of sinusoidal waveform and those employing pulsed current excitation [2]. CW detectors used in demining operations typically operate at a single frequency, which is convenient since relatively simple circuits can be used. On the other hand, discriminating different types of metals (e.g., aluminum detonator caps from steel coins) is not possible unless multiple excitation frequencies are applied [3], [8]. Moving

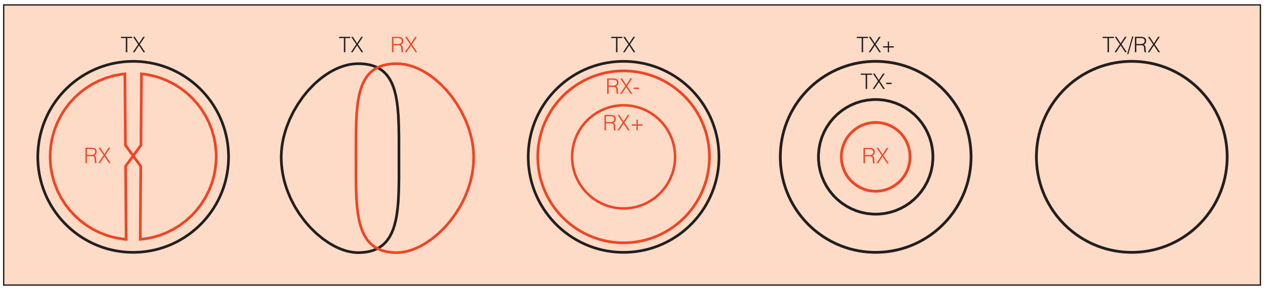

Fig. 1. Typical coil designs used in search heads of conventional metal detectors: receiver gradiometer design, double-D overlapping coils, coaxial design with a bucking receiver coil, coaxial design with a bucking transmit coil, and circular mono-coil design. Adapted from [5] (© 2020 IEEE).

towards spectroscopic detector operation would however require abandoning the traditional tuned-coil approach and adopting more complex signal generation methods, such as the ones relying on DDS techniques, or binary excitation with adequate spectrum-shaping properties.

In MDs employing pulsed excitation, a time decay of the secondary field induced by eddy currents is monitored after the transmitter has been shut off. Looking at different portions of the decay curve and observing its shape may reveal important information on a target's size and possibly metal type [8]. In general, EMI responses of smaller and less conductive targets are observable only in "very early" time portions of the response, so the ability to capture those signals could potentially open up new application areas such as detection of very thin wires or non-metallic parts typically found in improvised explosive devices. The engineering problem is to overcome the speed limitations related to inductive load switching, coil ringing, deep saturation of receive amplifiers, etc.

When it comes to the receiver side of MDs, microvolt-level signals are typically induced in the coil(s). Incorporating higher-resolution analog-to-digital (ADC) converters (≥ 16 bit) with sampling rates on the order of a few MS/s, as well as more powerful microcontrollers, could enable more efficient digital signal processing and thus more reliable formation of alarms. Latest generations of MDs have now incorporated such designs to overcome some of the difficulties related to analog-domain processing of the induced signals.

Finally, coil geometry of the detector's search head is another important factor influencing the overall performance of a particular MD. Specific geometries of conventional MDs, shown in Fig. 1, normally stem from various design trade-offs related to sensitivity, depth coverage, pinpointing ability, immunity to soil effects, etc. [2], [5]. Possible modifications to well-established coil geometries can be observed from two aspects. The first one is related to the problem of background interferences, e.g., the influence of magnetic (so-called non-cooperative) soils, where the goal is to maximize the ratio of signals corresponding to a metallic target of interest and soil. Designing proper metrics for the characterization and comparison of different coil designs is therefore crucial [4].

Another aspect for the possible optimization of the search head geometry comes into action if a detector is to be upgraded with target characterization of classification capabilities. In that context, it is important to come up with coil designs which would be able to induce different directional responses from the target, so that acquired EMI data can be used to recover information on a target's size, shape, orientation and metal type. Unfortunately, conventional search heads (Fig. 1) are by no means optimized for such purpose. Intuitively, coil arrays might provide data of higher quality / spatial diversity, but these are much more difficult to implement into practical handheld devices [5].

Feature Extraction Level

Extraction of a target's intrinsic features (i.e., the electromagnetic signature), independent of the target's relative location, orientation, or a particular type of search head, is a crucial step towards the implementation of a discrimination-enabled MD. For that purpose, approximate analytical models describing EMI scattering phenomena in metallic objects can be of vital help. In the widely-used induced dipole model, an object's intrinsic features are contained in six independent elements of the magnetic polarizability tensor [6], [7]. The task of dipole inversion is to estimate these tensor elements and the unknown target location from induced voltages obtained over a large number of known sensor positions (Fig. 2). This results in a well over-determined nonlinear inverse problem. The part introducing nonlinearity, and hence most difficulties with the inversion process, comes from dipole localization [5].

For a dipole-like metallic target, the signal of an EMI sensor, acquired over N different sensor positions is given by (1), where $\mathbf{u}_{\text{ind}}$ is N x 1 vector of induced voltages, $\mathbf{S}$ is the N x 6 sensitivity matrix, $\boldsymbol{\mathcal{M}}_{\text{v}}$ is a vector containing six independent elements of the target's magnetic polarizabiliy tensor (also referred to as directional magnetic polarizabilities), and k is the scaling term which depends on sensor's excitation parameters [5]. Column vectors of the sensitivity matrix $\mathbf{S}$ are called directional sensitivities, since they directly reflect the ability of a search head to induce the corresponding directional responses of a metallic target.

$$\mathbf{u}_{\text{ind}} = \begin{bmatrix} \mathbf{S}_{\text{xx}} & \mathbf{S}_{\text{xy}} & \mathbf{S}_{\text{xz}} & \mathbf{S}_{\text{yy}} & \mathbf{S}_{\text{yz}} & \mathbf{S}_{\text{zz}} \end{bmatrix} \cdot \begin{bmatrix} M_{xx} \\ M_{xy} \\ M_{xz} \\ M_{yy} \\ M_{yz} \\ M_{zz} \end{bmatrix} \cdot k = \mathbf{S} \cdot \boldsymbol{\mathcal{M}}_{\text{v}} \cdot k \quad (1)$$

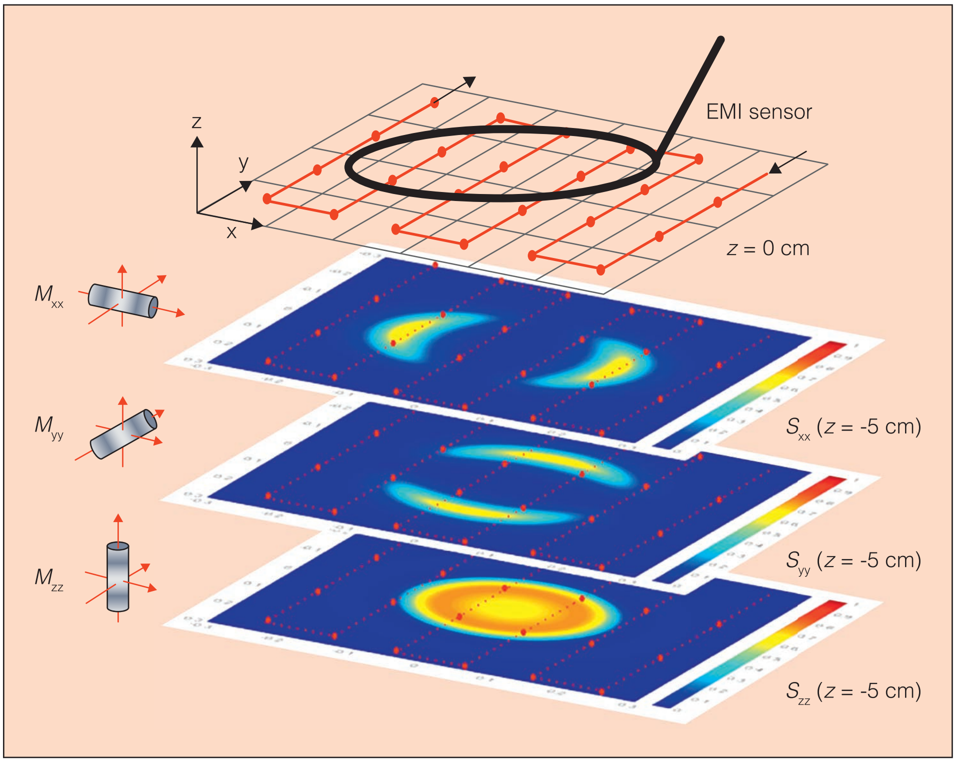

Fig. 2. Using a scanning metal detector to magnetically illuminate the target from different directions [5] (© 2020 IEEE).

Feature Interpretation Level

The theory behind the magnetic polarizability tensor is nowadays considered as well-established, and there is a common perception in the engineering community that the target's intrinsic features embedded within the tensor could provide good basis for discrimination between different classes of metallic targets, for a range of applications [8]. A simplified relationship between the tensor eigenvalues (observed at a single frequency) and the target's general shape and material type is given in Fig. 3 (eigenvectors are assumed to point towards x, y and z-axis). (These eigenvalues are obtained by arranging the elements of $\mathcal{M}_v$ into a symmetric 3x3 matrix and performing standard eigenvalue decomposition.)

An object having equal length along all of its three principal axes, such as sphere or a cube, responds equally in the x-, y- and z-direction, so $\lambda_{11} = \lambda_{22} = \lambda_{zz} = \lambda$, regardless if the target is magnetic or non-magnetic. On the other hand, non-uniformly shaped objects, i.e., objects having one or two dominant dimensions along their principal axes, respond distinctively different, depending on material type.

In case of a magnetic object, i.e., an object where magnetization effects are dominant with respect to eddy current effects, the response is strongest when the incident field is parallel to the principal axis that relates to the longest object's dimension. This means that the eigenvalues corresponding to those direction(s) would have higher magnitudes with respect to the others. For a magnetic rod oriented along the z-axis whose lengths in the x- and y-direction are negligibly small, only λ_{33} would be observed. Similarly, in case of a very thin magnetic disc or a quadratic plate placed in the x-y plane, the magnetic field would be equally concentrated in x- and y-directions only, and hence $\lambda_{11} = \lambda_{22} = \lambda$ while $\lambda_{33} \approx 0$ (Fig. 3).

For conducting and non-magnetic objects, the EMI response is strongest when the incident field is in such direction so that eddy currents circulate along their longest possible path. If we recall a simple right-hand rule relating magnetic field and a circular current loop, it follows that the strongest response would be induced when the incident field is perpendicular to the principal axis that corresponds to the longest object's dimension. In case of a thin non-magnetic disc, eddy currents circulate in the x-y plane only and hence $\lambda_{33} = \lambda$ and $\lambda_{11} = \lambda_{22} \approx 0$, while for a non-magnetic rod the eddy

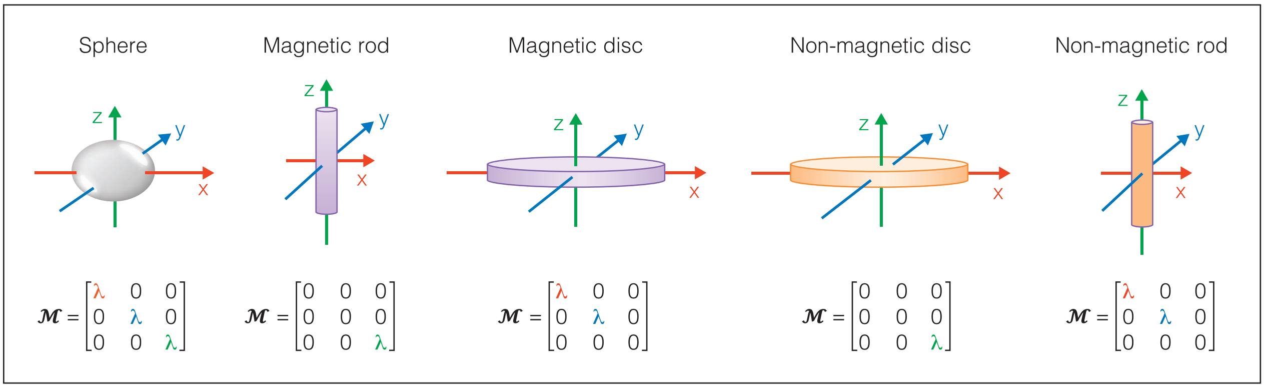

Fig. 3. Simplified interpretation of the magnetic polarizability tensor in terms of target's shape and material type.

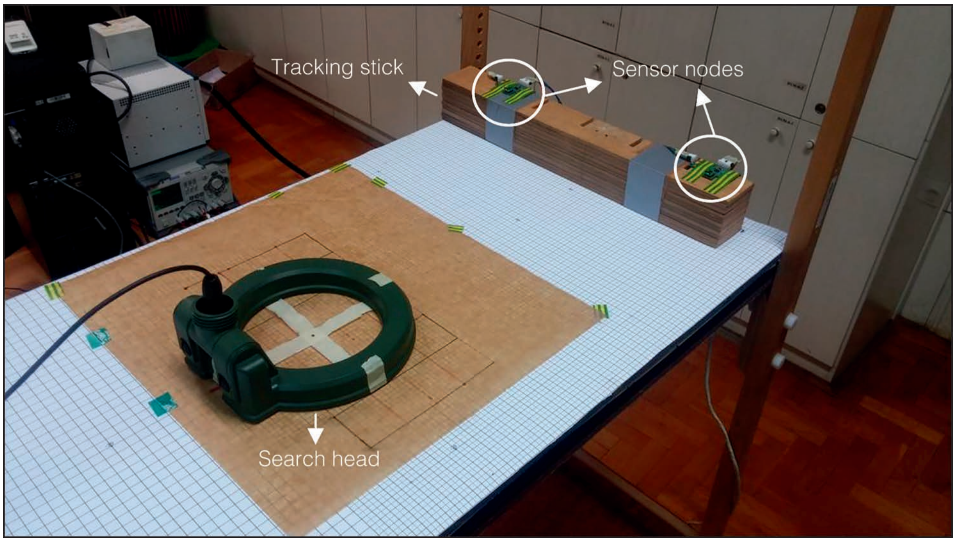

Fig. 4. Experimental laboratory set-up showing the detector's search head and the magnetic tracking system.

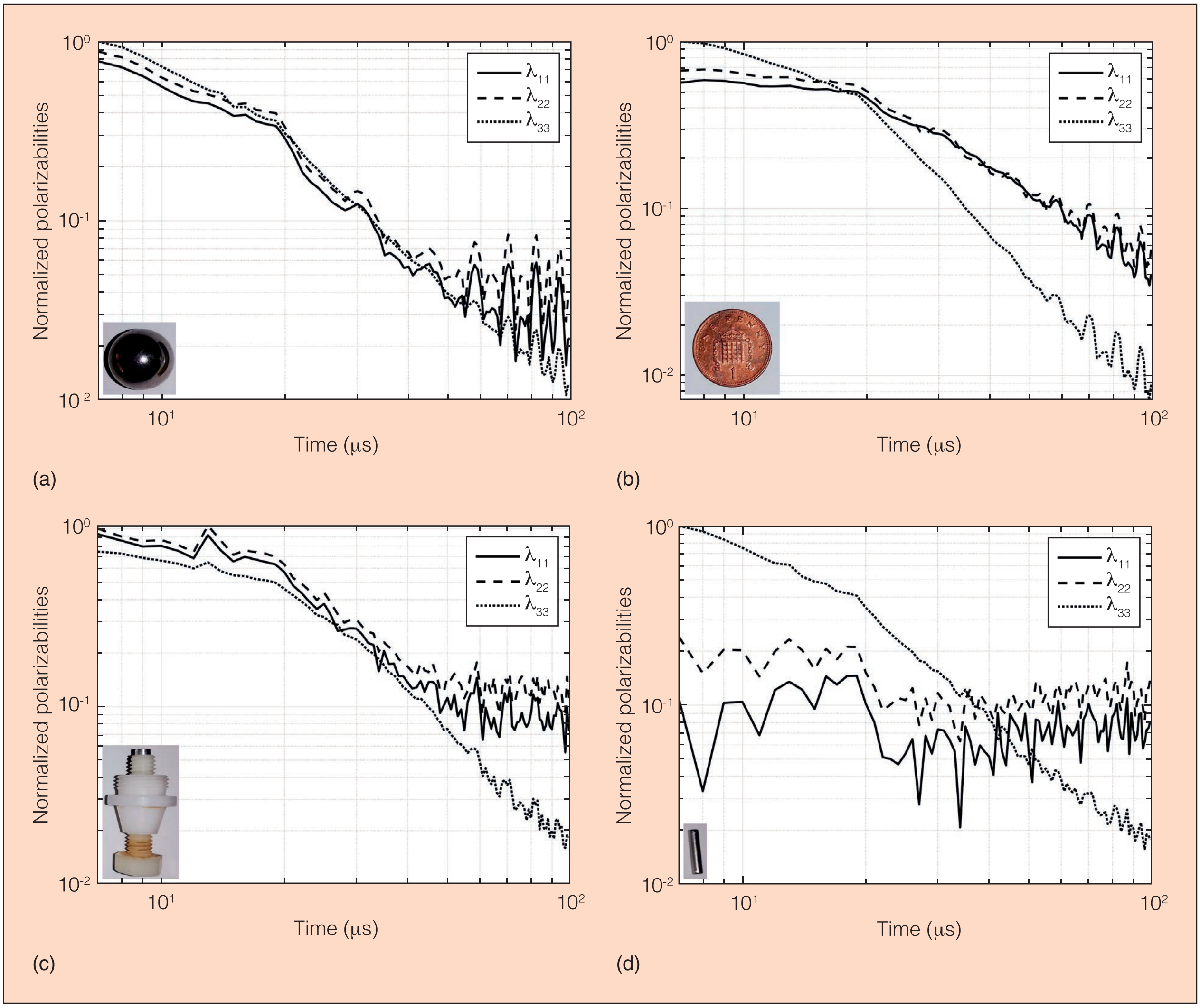

Fig. 5. Estimated tensor eigenvalues for: (a) a steel sphere; (b) 1 British Penny coin; (c) a PMA-2 landmine detonator simulant; and (d) a small steel cylinder.

current circulation is equal in x-z and y-z planes and therefore $\lambda_{11} = \lambda_{22} = \lambda$ and $\lambda_{33} \approx 0$.

As seen in Fig. 3, if the type of metal the target is made of is unknown, then there is a problem in determining the target's shape due to inherent ambiguity related to the mutual relationship of tensor eigenvalues obtained at a single frequency. Consequently, tensor eigenvalues obtained at multiple frequencies are required to reconstruct the target shape and metal type unambiguously, leading naturally to the application of tensor spectroscopy [3]. Similar conclusions apply to the case of pulsed detectors, where the decay curves of tensor eigenvalues are observed instead.

Example: Metal Detector Upgraded with Object Discrimination Abilities

Finally, we provide an illustrative example of the concepts presented so far, leading to the implementation of a discrimination-enabled MD. The experimental laboratory set-up is comprised of a pulsed MD featuring a circular mono-coil search head, a magnetic system for tracking the position and orientation of the search head, and a dipole inversion algorithm implemented on a PC (Fig. 4). The search head is moved by hand over a wooden testing platform, under which different metallic targets are mounted. Inversion results are shown in Fig. 5.

In case of a spherical target, all three eigenvalues seem to be approximately equal during the whole time window. At later time instances ($t > 50$ µs), the estimates become too noisy due to low signal to noise ratio.

Inverted tensor eigenvalues corresponding to a coin clearly indicate two equally strong responses in the transverse direction (λ_{11} and λ_{22}) and a weaker response in the axial direction (λ_{33}). Different slopes of decay curves suggest that the responses come from a magnetic target, which is true since the coin is made of copper plated steel. Consequently, the results lead to a conclusion that the target features a plate-like shape. At the early-time portion of the curve (i.e., for $t < 50$ µs), the copper-plated coin behaves like a nonmagnetic plate, since the eddy currents induced in the copper overshadow the magnetization effects due to lower skin depth. At later time instances, which correspond to lower frequencies in the excitation spectrum, magnetic features become dominant.

For the case of a PMA-2 landmine detonator simulant, which is in fact a hollow aluminum cylinder with a relatively small aspect ratio, the eigenvalues corresponding to target's transverse response (λ_{11} and λ_{22}) are approximately equal and somewhat larger compared to the eigenvalue corresponding to target's axial response (λ_{33}). Furthermore, decay curves of all three eigenvalues are of similar shape (for $t < 50$ µs), indicating the nonmagnetic nature of the target [9].

A small ferromagnetic cylinder exhibits the behavior opposite to that of an aluminium cylinder, i.e., the response is the strongest in the axial direction (λ_{33}), while the transverse responses (λ_{11} and λ_{22}) are significantly lower and approximately equal. Different slopes of axial and transverse eigenvalues indicate clearly that the target is magnetic [9].

Conclusions

In this paper, we have shown how innovative, next-generation I&M systems can be devised by taking advantage of new scientific and technological advancements, while retaining a strong foundation in fundamental knowledge and industry's accumulated know-how. This is illustrated on a practical case in humanitarian demining, where analytical modeling, stemming from first principles electromagnetism, is applied to a rather simple metal detection device in order to upgrade it with advanced metal discrimination capabilities.

Acknowledgement

The authors would like to thank the Sir Bobby Charlton Foundation for supporting the research reported in this paper.

References

[1] "Landmine Monitor 2018," International Campaign to Ban Landmines (accessed Oct. 2019). [Online]. Available: http://the-monitor.org/media/2918780/Landmine-Monitor-2018_final.pdf.

[2] D. Guelle, A. Smith, A. Lewis, and T. Bloodworth, *Metal Detector Handbook for Humanitarian Demining*, Luxembourg: Office for Official Publications of the European Communities, 2003. [Online]. Available: https://www.nolandmines.com/PDF_files/MetalDetectorHandbook.pdf.

[3] A. J. Peyton and D. Daniels, "Detecting landmines for a safer world," *Ingenia Online,* issue 75, Jun. 2018. [Online], available at: https://www.ingenia.org.uk/Ingenia/Articles/2f67b8a4-4fee-4fc2-88d7-f0c535b0dc89.

[4] M. A. Reed and W. R. Scott, "Optimization and analysis of wire-wound coil heads for EMI systems," *IEEE Sens. J*., vol. 19, no. 5, pp. 1672-1682, Mar. 2019.

[5] D. Ambruš, D. Vasić, and V. Bilas, "Comparative study of planar coil EMI sensors for inversion-based detection of buried objects," *IEEE Sens. J*., vol 20, no. 2, pp. 968-979, Sep. 2019.

[6] T. H. Bell, B. J. Barrow, and J. T. Miller, "Subsurface discrimination using electromagnetic induction sensors," *IEEE Trans. Geosci. Remote Sens*., vol. 39, no. 6, pp. 1286-1293, Jun. 2001.

[7] C. E. Baum, Ed., *Detection and Identification of Visually Obscured Targets*. New York, NY, USA: Taylor & Francis, 1999.

[8] D. Ambruš, "Detection of low-metallic content landmines based on electromagnetic induction model," Thesis for Doctoral degree, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia, 2019. Summary [Online]. Available: https://urn.nsk.hr/urn:nbn:hr:168:453778.

[9] F. Shubitidze, K. O'Neil, K. Sun, and K. D. Paulsen, "Investigation of broadband electromagnetic induction scattering by highly conductive, permeable, arbitrarily shaped 3-D objects," *IEEE Trans. Geosci. Remote Sens*., vol. 42, no. 3, pp. 540-556, Mar. 2004.

Davorin Ambruš (Davorin.Ambrus@fer.hr) is a Postdoctoral Researcher at the University of Zagreb, Faculty of Electrical Engineering and Computing. He received his Dipl.Ing., M.Sc. and Ph.D. degrees in electrical engineering from the University of Zagreb, Croatia in 1999, 2005, and 2019, respectively. His research interests are in the fields of computational electromagnetic sensing, sensor electronic systems and signal processing.

Darko Vasić is a Professor with the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. He received the Dipl. Ing., M. Sc. and Ph. D. degrees in electrical engineering from the University of Zagreb, Croatia in 2002, 2005, and 2010, respectively. His research interests are in the field of electronic instrumentation and signal processing, specifically electromagnetic measurement methods, networked sensors, signal detection and inverse problems.

Vedran Bilas is a Professor with the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, where he is also the Head of the Laboratory for Intelligent Sensor Systems. He has over 20 years of research, development and technology transfer experience in the area of sensors and electronic systems. His current research interests include inductive methods, intelligent sensors, sensor modeling, low power sensing and wireless sensor networks.