Upgrading Metal Detection to Metallic Target Characterization in Humanitarian Demining

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Abstract

Conventional metal detectors used in humanitarian demining feature high sensitivity to extremely low quantities of metal, such as those found in low-metallic content landmines. On the other hand, enormous false alarm rates (up to 1,000 alarms per mine) are introduced, due to detectors inability to discriminate between metallic parts of a mine and non-hazardous metallic clutter. If metal detectors could be upgraded such as to provide information on target's size, shape, position, orientation and material properties, false alarm rates could be significantly reduced. In this paper, we present the basic concept of model-based metallic target characterisation (MTC) and the related work of our research group. Also, we discuss some practical implications of the proposed methodology with respect to its possible deployment in the field: either in a form of handheld device or for mounting on robotic platforms.

1. Introduction

In spite of recent developments in landmine detection technologies for humanitarian demining, metal detectors still remain the tools of choice when it comes to close-in detection in the field [1]. Metal detectors are devices that operate on a well-known principle of low-frequency electromagnetic induction (EMI). Although commercial devices differ in terms of their technical and implementation details (such as excitation type, signal processing, soil compensation techniques, etc.), the operating principles and basic functionalities are essentially the same.

Conventional metal detectors are sensitive to extremely low amounts of metal such as those found in low-metallic content landmines. On the other hand, enormous false alarm rates (up to 1,000 alarms per mine) are introduced, due to detectors inability to discriminate between metallic parts of a mine and non-hazardous metallic clutter. Since the high probability of detection is a top-priority requirement in humanitarian demining, recent developments of metal detectors have been predominantly focused on increasing their detection sensitivity, enhancing performance in non-cooperative soils and improving other technical features such as power consumption and device ergonomy.

At the same time, the problem of false alarms resulting from metallic clutter has often been seen as a nuisance and an inevitable side-effect of the humanitarian demining process. Such observation is usually attributed to scenarios where the mine suspected area needs to be completely cleared from all metallic objects (both mine and clutter), as required by actual regulatory procedures. However, there are many cases where such requirements are almost impossible to implement and where the false alarm rate problem should be addressed in order to improve the overall speed, cost and safety of humanitarian demining.

In both cases, a deminer would clearly benefit from a detector featuring additional target information that goes beyond simple audible metal detection signal. The characterisation of metallic target should be implemented in such a way that the target could be classified as potentially hazardous or non-hazardous with a sufficient confidence level. Such information would be helpful with the final "mine-clutter" and "dig-no dig" decisions, but also during confirmation and excavation phase. It is important to note that the concept of metallic target characterisation (MTC) is fundamentally different from multi-sensor detection systems that have been employed recently (e.g. tools that combine metal detectors with ground penetrating radars (GPR), explosive detectors, etc.). Instead of using mine detectors of different sensing modalities, in the proposed approach a single (EMI) modality is used to extract information on target geometrical and electromagnetic properties.

2. Metallic target characterisation concept

In the context of EMI-based landmine detection, MTC refers to getting information on targets:

- average size,
- shape (principal axes aspect ratio),
- spatial orientation,
- relative 3D position,
- material properties (electrical conductivity and magnetic permeability).

If the given information could be estimated from actual sensor data acquired during scanning over the target area, it could serve as a reliable basis for further target classification and identification process. From a practical point of view, most landmines have some common features with respect to the aforementioned properties: vertically or horizontally oriented firing pins (mostly of cylindrical shape), small burial depth (up to 20 cm), etc. Furthermore, it is reasonable to assume that only a limited number of different types

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of landmines would be present on a particular mine suspected area. Therefore, the complexity of the initial “mine-clutter” problem could be significantly reduced.

2.1. State-of-the-art in MTC

MTC techniques that utilize analytical EMI-based models have proved to be very effective for a range of problems in security, geophysical surveys and non-destructive testing (NDT) applications. Physics-based models are used to describe the relationship between the EMI response of a detector and the geometrical and electromagnetic properties of a target. Model parameters, obtained from data observations through estimation (inversion) procedures, can be used to extract the information needed for classification and identification purposes.

Different analytical models and corresponding inversion procedures that relate to the MTC problem have been reported in literature. Most of these methods are (to some extent) based on the magnetic dipole approximation, which enables computationally efficient parameter estimation, capable of operating in real-time. These methods can be roughly classified in the two main categories: methods relying on the induced dipole model [2] and methods based on a discrete number of spatially distributed magnetic dipoles [3]. While the former methods are well suited for relatively small metal targets (such as low-metallic content landmines), the latter methods are required when dealing with larger and possibly heterogeneous targets such as unexploded ordnance (UXOs).

Induced dipole model and related inversion techniques have been successfully applied for real-time detection, localization and identification of hidden metallic objects in walk-through scanners for airport security [4]. Within the UXO research community, several sophisticated instruments using complex dipole-based models and fast inversion techniques were recently designed [5]. However, to the best knowledge of authors, there are still no commercial devices utilizing the principle of model-based MTC for application in humanitarian demining. Adaptation of such methods for landmine detection brings a number of research challenges. One of the major challenges is the optimization of inversion procedures and sensor geometry with respect to the operation in environments with low SNR (signal-to-noise ratio).

2.2. Induced dipole model

The induced dipole model assumes the buried target’s size to be much smaller than the size of a detector coil. Therefore, if the object is not too close to a detector, it can be treated as a single magnetic dipole and described by the magnetic polarizability tensor of rank 2, i.e. the 3x3 symmetric polarizability matrix [3]. Basic mathematical description of the model is given by expressions (1)-(3).

$$\vec{m}_{\text{target}} = \overleftrightarrow{M}\vec{H}_{\text{prim}}(\vec{r}_{\text{TX}} - \vec{r}_{\text{target}}) \tag{1}$$

$$\vec{H}_{\text{sec}}(\vec{r},\vec{r}_{\text{TX}},\vec{r}_{\text{RX}}) = \frac{1}{4\pi|\vec{r}|^3}\left(\frac{3\vec{r}(\vec{r}\cdot\vec{m}_{\text{target}})}{|\vec{r}|^2} - \vec{m}_{\text{target}}\right) \tag{2}$$

$$\vec{u}_{\text{RX}} = f_{\text{FWD}}(\overleftrightarrow{M},\vec{r}) \tag{3}$$

The target magnetic moment $\boldsymbol{m}_{\text{target}}$ is linearly proportional to the primary magnetic field $\boldsymbol{H}_{\text{prim}}$ via polarizability matrix $\boldsymbol{M}$, (1). The secondary field $\boldsymbol{H}_{\text{sec}}$, sensed by the receiver coil, is essentially the magnetic field of a dipole, (2). From (1) and (2) a forward function is obtained, (3), describing the relationship between the receiver coil voltage $\boldsymbol{u}_{\text{RX}}$, magnetic polarizability matrix $\boldsymbol{M}$ and the target position $\boldsymbol{r}$.

2.3. Estimation of target geometry and material properties

In order to characterise the target using the induced dipole model, the parameters of a model ($\boldsymbol{M}$, $\boldsymbol{r}$) need to be estimated first by fitting the measured voltages $\boldsymbol{u}_{\text{RX}}$ to model predictions. Since the inversion problem is nonlinear (in terms of $\boldsymbol{r}$), the solution can be found by applying some of the nonlinear optimization algorithms based on the least-squares criterion, (4).

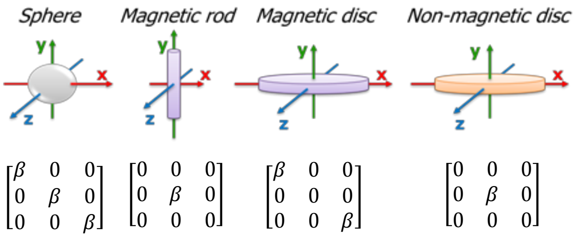
$$\arg\min\left(\left\|\vec{u}_{\text{meas}} - f_{\text{FWD}}\left(\overleftrightarrow{M},\vec{r}\right)\right\|^2\right) \tag{4}$$

The relative target position $\boldsymbol{r}$ follows from the inversion procedure directly. Other target properties can be obtained from a diagonalized form of the polarizabilty matrix $\boldsymbol{M}$, (5), (6).

$$\overleftrightarrow{M} = \overleftrightarrow{R}^T(\theta,\phi)\overleftrightarrow{\beta}(\omega)\overleftrightarrow{R}(\theta,\phi) \tag{5}$$

$$\overleftrightarrow{\beta} = \begin{bmatrix} \beta_x(\omega) & 0 & 0 \\ 0 & \beta_y(\omega) & 0 \\ 0 & 0 & \beta_z(\omega) \end{bmatrix} \tag{6}$$

The spatial orientation of a target can be derived from the rotation matrix $\boldsymbol{R}$. On the other hand, information on the target size, shape and material properties are contained in frequency-dependent eigenvalues of $\boldsymbol{M}$, $\beta(\omega)$. Some of the basic principles of estimating target geometry and material properties from the polarizability matrix are given in Figure 1.



$$\begin{bmatrix} \beta & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \beta \end{bmatrix} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} \beta & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta \end{bmatrix} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Figure 1. Basic principles of estimating target geometry and material properties from the magnetic polarizabilty matrix.

3. Experimental research

Based on the previously described MTC methodology, experimental research was conducted by the Advanced Instrumentation Group (AIG, University of Zagreb, FER-ZESOI). The research is conducted within the framework of the project DEMINED, aimed at the development of a next-generation EMI detector for landmine detection in humanitarian demining [6].

Experiments were conducted on laboratory samples of test targets that correspond to metallic content typical of a class of landmines, in accordance with the CWA-14747 standard [7], Figure 2.a. Test targets include spheres, cylinders and tubes of different geometries and materials (steel, aluminium, copper, etc).

Figure 2. a) Laborartory test samples (ITOPs), b) commercial landmine fuze (UPMAH-2).

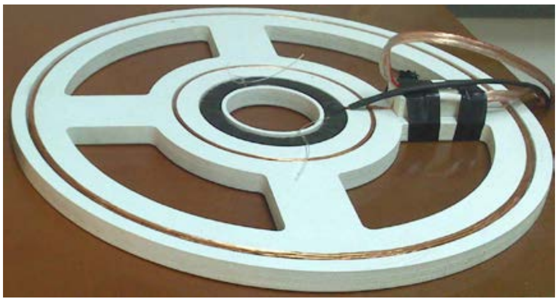


Figure 3. Laboratory prototype of a sensing head.

Measurements on commercial mine fuzes (explosive-free), Figure 2.b, shall also be performed in order to validate the methodology with real-world targets.

The experimental set-up is comprised of a laboratory sensing head prototype [8], Figure 3, non-metallic testing stand with measurement grid, some custom-designed electronic circuitry, standard laboratory instruments and high-speed data acquisition devices. Experiment control, digital signal processing, modelling and inversion procedures are implemented in MATLAB, Figure 5. An illustrative example of an experiment covering a rather simple characterisation of a steel sphere is shown in Figure 4.

Future experimental work will focus on inversion procedures for the estimation of target position and magnetic polarizability matrix, optimized with respect to execution speed and low SNR. The ultimate goal is to develop a field-deployable demonstrator device.

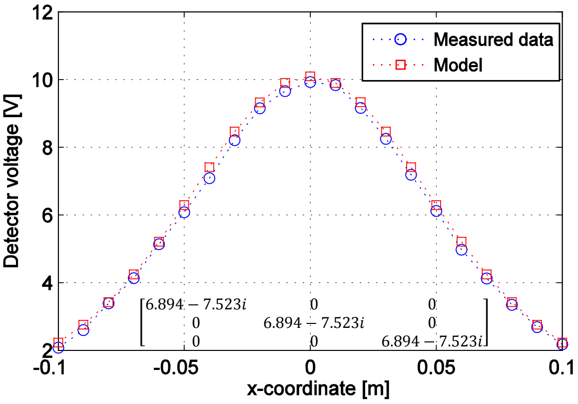
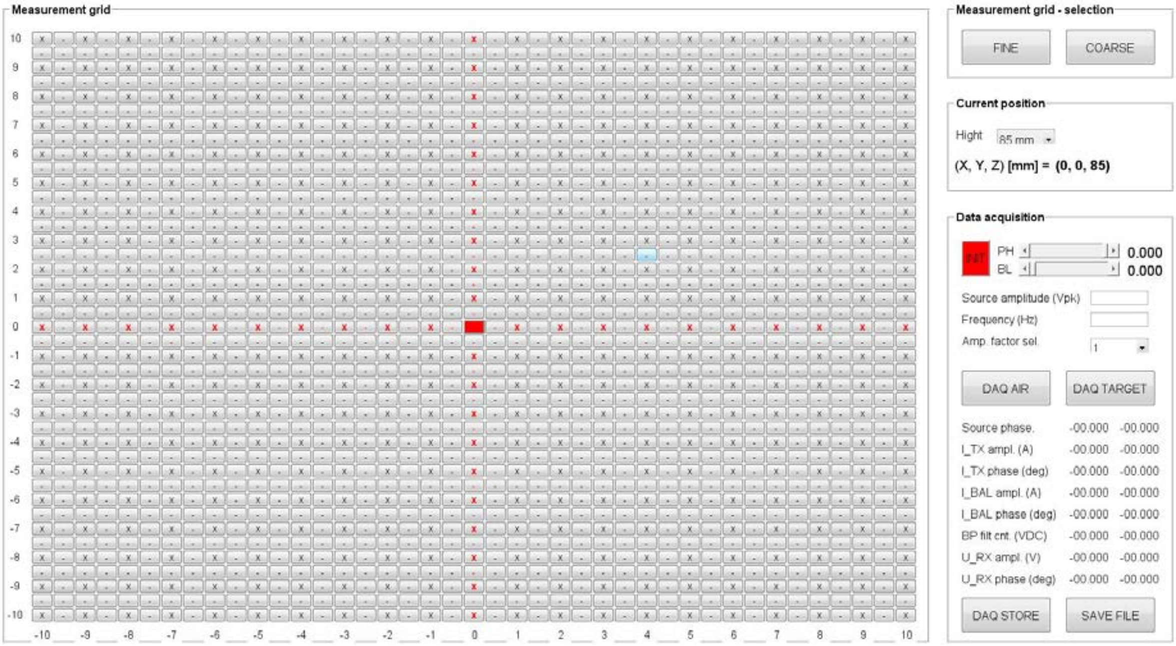


Figure 4. Modeled and measured EMI responses of a steel sphere (10mm diameter) with inverted polarizability matrix (at 50kHz).



Hight 85 mm

(X, Y, Z) [mm] = (0, 0, 85)

PH 0.000

BL 0.000

Source amplitude (Vpk)

Frequency (Hz)

Amp. factor sel. 1

Source phase -00.000 -00.000

I_TX ampl. (A) -00.000 -00.000

I_TX phase (deg) -00.000 -00.000

I_BAL ampl. (A) -00.000 -00.000

I_BAL phase (deg) -00.000 -00.000

BP filt cnt. (VDC) -00.000 -00.000

U_RX ampl. (V) -00.000 -00.000

U_RX phase (deg) -00.000 -00.000

Figure 5. Graphical user interface of the application program for conducting experiments with test targets (MATLAB).

4. Towards deployment in the field

For a practical implementation of next-generation EMI devices featuring the MTC concept in a real-field scenario, there are several technical challenges that need to be addressed. One of the major ones is a problem of tracking the relative position and spatial orientation of the detector's sensing head during its scanning motion over the suspected area. This information should be made available to the inversion algorithm in real-time since different sensing head positions (relative to the position of a target) are used to obtain the complete set of observations, required for reliable inversion.

The position and orientation of the sensing head should be determined with respect to its local coordinate system, which could be either stationary (using ground as reference) or dynamic (i.e. referenced to a deminer or a robot). In case the sensor is mounted on a robotic vehicle, its position and orientation are clearly defined in a robot coordinate system by the kinematics of a manipulator. On the other hand, if a handheld device is used, a separate tracking system has to be provided. Different approaches have been proposed and evaluated for this particular problem, such as inertial sensors, optical systems using visual markers and stereo cameras, ultrasonic localization systems, EMI-based methods, Figure 5, etc. Optimal tracking system would provide sub-centimetre accuracy, high update rate (in milliseconds range), minimum complexity and unobtrusiveness.

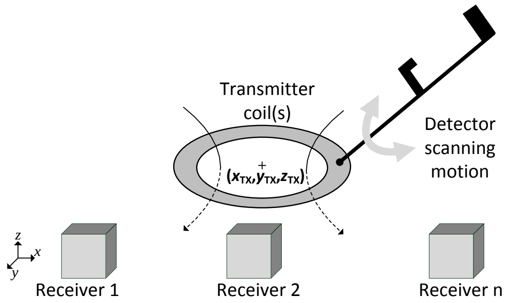


Figure 5. Principle of EMI-based method for sensing head tracking.

Another issue when it comes to the implementation of MTC concept in humanitarian demining is the preferred mode of operation. For manual detection, a two-step procedure is envisaged. In the first phase, a device would operate in a standard, deminer-familiar metal detector mode. After a detection signal is obtained, a deminer could simply switch the device into the MTC mode and use the additional target information for its decision on how to proceed. On the other hand, for robotic applications, such approach is not necessarily the most effective. The choice actually depends on objectives and requirements of a particular robotic mission and involves a number of different issues such as path planning, type of environment, etc.

5. Conclusion

In order to overcome the well-known limitations of existing metal detector technology in terms of false alarm rates, a new mine detection concept relying on model-based metallic target characterisation (MTC) is proposed. Such concept has already been verified in other applications, such as security and UXO detection, which provides strong motivation for its potential application in humanitarian demining. Initial results of our experimental work in this field suggest that the proposed concept could lead to a new enabling technology for developing next-generation detection devices – either in the form of manual mine detectors or for integration with robotic systems.

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