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Improved Landmine Discrimination With an Off-the-Shelf Metal Detector

Marc Freese
Tokyo Institute of Technology

Edwardo Fukushima
Tokyo Institute of Technology

Shigeo Hirose
Tokyo Institute of Technology

Improved Landmine Discrimination With an Off-the-shelf Metal Detector

While improvement has been made with metal detectors in detection depth and ground rejection, little effort has been directed toward better discrimination capabilities; high false-positive rates not only increase clearance time, they tend to lower deminer vigilance, causing accidents. The authors have modeled a statically operating, off-the-shelf metal detector by generating volumetric sensitivity profiles. They present in-laboratory measurements and results of experiments on a test demining site in Cambodia. This article aims at giving deminers a more informed view of metallic targets, allowing them to take differentiated actions during target identification and removal.

by Marc Freese, Edwardo F. Fukushima and Shigeo Hirose [Tokyo Institute of Technology]

Metal detectors usually rely on a pair of coils, one of which transmits either a pulse or a continuous electromagnetic waveform. This signal induces eddy currents in buried metallic objects, creating a secondary electromagnetic field detected by the receiver coil. MDs with modest discrimination capabilities exist and have been traditionally used for "treasure hunting" and in the mining industry; however, tuning MDs for landmine searching is delicate due to the dangerous nature of landmines. For that reason, MDs developed to locate landmines do not offer discrimination capabilities, translating to a high rate of false-positives. Landmine-affected regions see a higher-than-usual presence of metal scraps and other fragments. This clutter represents an important time penalty in the demining process, dramatically increasing costs and tending to desensitize deminers to the ever-present danger of explosion.

Improving an MD's discrimination capabilities is a multi-faceted problem to consider. Target material recognition is typically used in the mining industry, but target shape and size recognition as well as depth determination can also allow for better discrimination strategies. In the past, some research effort has been made in improving detector hardware by using multi-receiver coils[1] or in using standard MDs for gaining depth information by analyzing the curve of a typical scan pass.[2] Target shape reconstruction has also been investigated where a restoration filter determines a target's shape from raw MD images.[3] The depth at which the restoration filter is effective is one concern, however.

This paper describes an approach with a standard MD that allows performing discrimination for a class of metallic targets that are relatively small and isotropic, including metallic components of mines. The approach considers first the MD's three-dimensional sensitivity profile

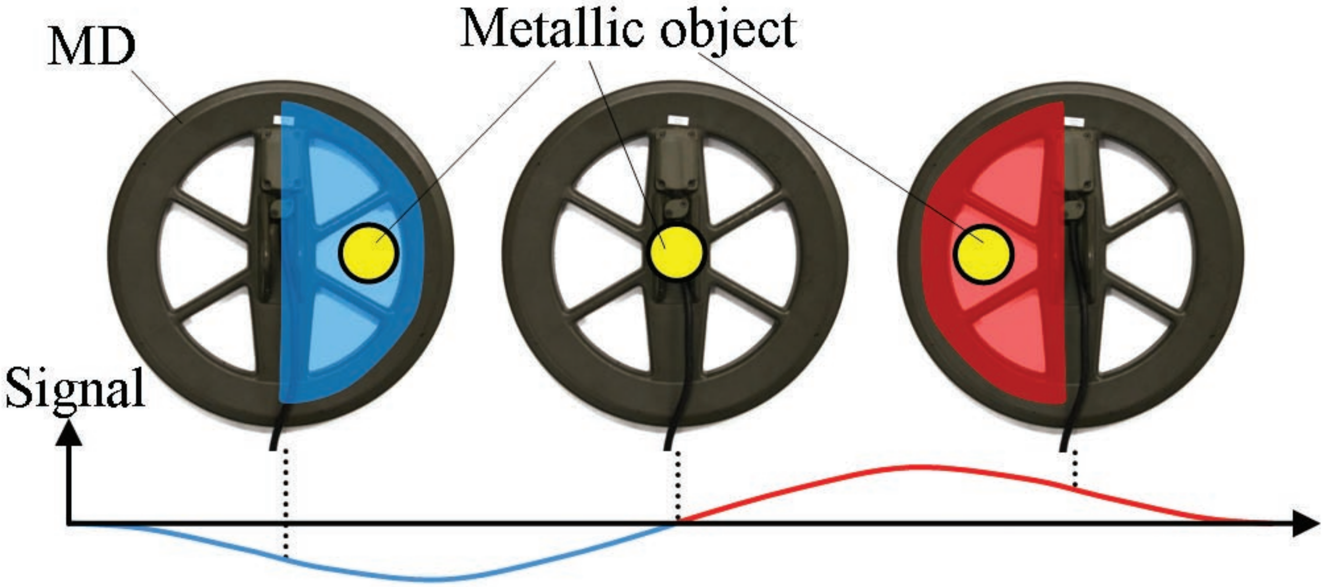

Figure 1: MIL-D1 metal detector signal depending on target position.
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(or footprint[4]) for a target representing the typical metal content of a class of landmines. Second, the experiment tries matching acquired MD image data with the sensitivity profile gathered in step one using two cross-correlation calculation methods. If the outputs of the calculations, which represent target burial depths, lay within a certain tolerance, then the target is a true positive—otherwise the target is considered a false positive. The result of the calculations can also be used in a more differentiated way, allowing the deminer to adjust his/her behavior according to the likeliness of a target to be a landmine. This fine-tuning should improve deminers' safety.

Experiments have been conducted with a commercially available MD in the laboratory first, then at a test demining site in Cambodia to assess practicality in near-real-world conditions. The effect of different types of soil was also investigated using sand, laterite and clay soils.

Discrimination Method

The discrimination method is based on two simple observations:

1. Raw MD images can be used to extract depth information if the target is known: for a given target, the burial depth (or distance to the MD) is a function of the MD's signal maximum amplitude.
2. Normalized MD images for a large variety of targets are relatively similar for corresponding depths: The burial depth is a function of the MD's normalized signal pattern.

The above observations allow us to obtain two different target burial depths—one is target-dependent; the other is not. If the calculation method dependent on the target is tuned appropriately (e.g., tuned to accurately detect the depth of a target landmine), the difference of the two calculated values allows us to conclude that the target is not the searched landmine. The discrimination method is presented and tested with a commercially available MD but can also be used with other types of MDs, given certain restrictions discussed later.

MIL-D1 Metal Detector. The MIL-D1 model (*Costruzioni Elettroniche Industriali Automatismi* [CEIA], Arezzo, Italy) is commonly used by humanitarian and military deminers. Based on two side-by-side coils (or "double-D" configuration), the left coil delivers a negative signal that is combined differentially with the positive signal from the right coil. Figure 1 on the previous page shows the operation principle of the MIL-D1.

The obtained MD images depend on various factors such as target shape, size, material, orientation and burial depth. In a less significant way they also depend on soil type. Figure 2 shows the normalized MD images at various depths for an 11-mm stainless steel ball.

Target metallic objects. While flat, long or relatively large targets can produce different images, we notice that for rather small and isotropic objects, similarities with patterns shown in Figure 2 are important. Metallic objects of such a target class are shown in Figure 3 and were used throughout the experiments. They include stainless steel balls (3mm, 5mm and 11mm), an aluminum cylinder (11mm in diameter and 21mm in length) and an International Test Operations Procedure insert, a

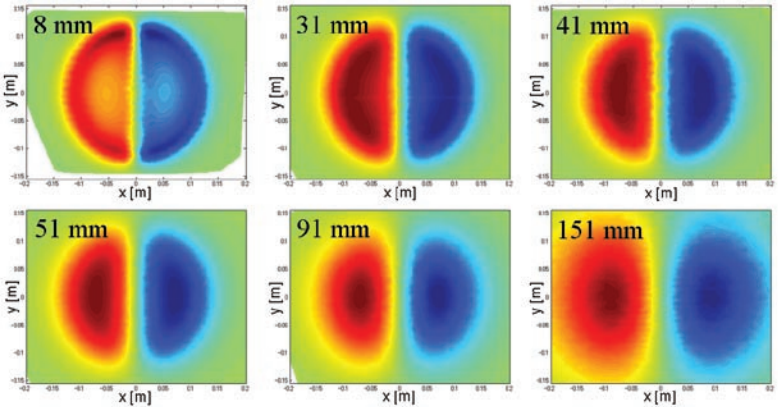
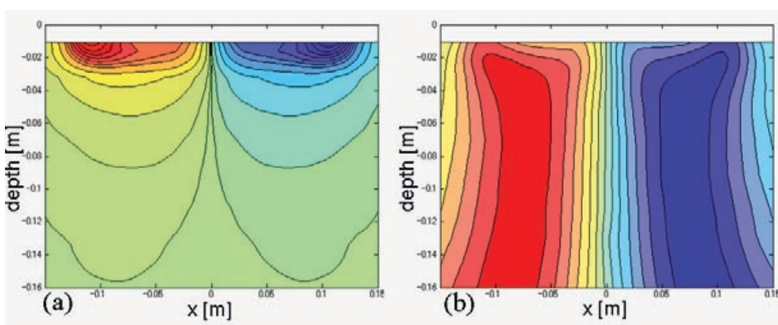


Figure 2: MIL-D1 imaging of an 11-mm stainless steel ball at various burial depths.

Figure 3: Metallic targets used for the discrimination experiments.



Figures 4a and 4b: Cut through the MD's sensitivity profile for (a) an 11-mm ball and (b) a corresponding, z-axis-normalized sensitivity profile.

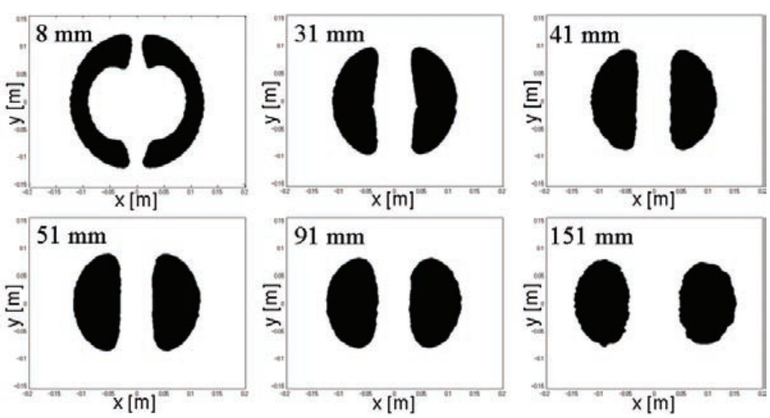


Figure 5: Cut through the MD's sensitivity mask (along the x-y plane) for the 11-mm ball at various depths.

standard target that represents the metal content of a class of anti-personnel landmines and allows safe experimentation (called an ITOP or an ITOP insert).[5]

The ITOP and aluminum cylinder, generating slight anisotropic responses, remain vertical. The goal of the experiments conducted was to discriminate the vertical ITOP from other targets. Depth is always measured as the distance from the bottom surface of the MD to the center of the target.

Target-dependent burial depth calculation. The MD's sensitivity profile for the five targets was generated by acquiring MD images at various depths, then by interpolating data between slightly smoothed images to obtain a dense three-dimensional matrix. A cut through the matrix (along the x-z plane) is shown in Figure 4a (see previous page). Figure 4b shows the same cut through the matrix that is normalized at each depth level.

The sensitivity profile is used as a comparison reference to compute a burial depth for an input image of an unknown target. The best match along the vertical axis of the sensitivity profile with the input image is used to determine a burial depth. The following cross-correlation product (sum of squared differences) is used to determine the best match:

$$(f \otimes g)(x,y) = \sum_i \sum_j (f(i,j) - g(x+i,y+j))^2$$

Here *f* is the raw input image, *g* is a slice in the sensitivity profile at a given depth and *x* and *y* are horizontal shift amounts. Practically, for each depth value, several cross-correlation products are calculated around the 0-position, varying the x-y offsets. Then, taking a set of the smallest values along the vertical axis, we obtain a distribution that indicates a burial depth. If the target is identical to the object used to generate the sensitivity profile, the burial depth will be accurate; otherwise it might be off by several centimeters.

Target-independent burial-depth calculation. The sensitivity profile obtained in previous section is used to generate another three-dimensional matrix, hereafter referred to as the sensitivity mask; for each depth layer in the sensitivity profile, the strongest amplitudes in an image are kept to form a binary image as can be seen from Figure 5 (see previous page). The sensitivity mask gives a simplified signal pattern description.

As for the sensitivity profile, the sensitivity mask is used as a comparison reference to compute a burial depth for an unknown target. The best match along the vertical axis of the sensitivity mask with a modified input image (as for the sensitivity mask, the raw input image is first turned into a binary image) is used to determine a burial depth. The following cross-correlation product (sum of products) is used to determine the best match:

$$(f \otimes g)(x,y) = \sum_i \sum_j f(i,j) \cdot g(x+i,y+j)$$

with *f* being the modified input image, *g* being a slice in the sensitivity mask at a given depth and *x* and *y* being horizontal shift amounts. Taking a set of the biggest values along the vertical axis, we obtain a distribution that indicates a burial depth. Given a reasonable tolerance, this burial depth is always accurate and does not depend on the tested target.

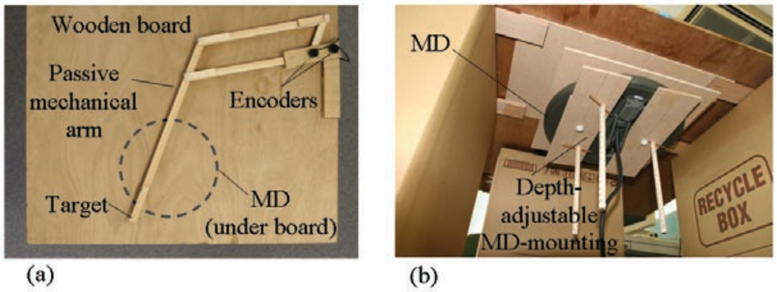


Figure 6: Metal-free position acquisition device for MD imaging as seen (a) from above and (b) from below.

Discrimination value calculation. The above two sections resulted in two different burial depths for a tested target. The idea, when searching for a given landmine, is to use the landmine to first create a corresponding sensitivity profile and sensitivity mask. That will then be used on input images (obtained from blind scanning) to compute the above two burial depths. The discrimination value is obtained by taking the difference of the two burial depths; the closer to zero, the higher the chance the scanned target is a landmine of the searched type.

In-laboratory Experiments and Results

To be able to acquire high-quality MD imaging data with as little disturbance as possible, a non-metallic position-acquisition device was developed (see Figure 6). It consists of a wooden board under which the MIL-D1 MD is attached. During data acquisition, the MD stays fixed, eliminating common disturbances.

Experiment set-up. The target to be tested is attached at the tip of a passive mechanical arm that records its x-y position when manually swept by the user. Data is displayed and the user can quickly detect accidental holes in the raster pattern and correct them, keeping a regular data density of at least 40,000 points/sq m.

Results. All five targets' images were recorded with the position-acquisition device at several depths to obtain input images to test the discrimination capabilities of the proposed method. Measurements were preceded by an MD reset procedure to ensure the same initial conditions. Since the proposed experiment was to discriminate the ITOP (e.g., landmine) from the other targets shown in Figure 3 (see previous page), the ITOP was measured twice at each depth—once to obtain input images to test the discrimination method and a second time to obtain data to generate the sensitivity profile and mask for the ITOP. Recorded images where noise levels became apparent or when the MD became saturated (aluminum cylinder at a shallow depth) were discarded.

Figure 7 shows results obtained with the target-dependent burial depth calculation method. The ITOP shows precise depths with a maximum error of 4mm. The other curves can only be evaluated subjectively since they don't correspond to an actual depth. We can, however, note that they look relatively regular and noise-free.

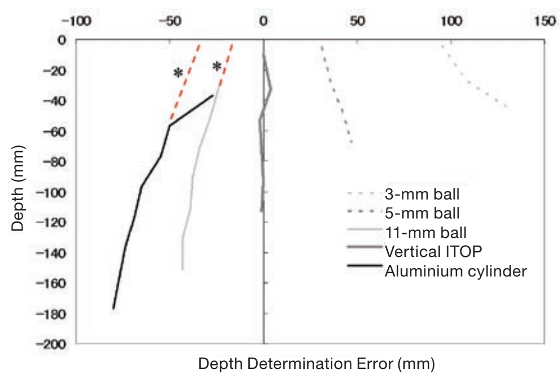


Figure 7: Depth determination errors for the target-dependent burial-depth calculation method. Dashed curves indicate the change obtained for the aluminum cylinder and 11-mm ball if the ITOP's sensitivity profile was extended upwards.

The 11-mm steel ball and the aluminum cylinder, generating wider signal amplitudes than the ITOP at a given depth, produce erroneous results at shallow depths; indeed, the ITOP's sensitivity profile doesn't offer appropriate matches at considered depth levels. To avoid this problem, the ITOP's sensitivity profile can be extrapolated upwards. This operation doesn't bias results as it only produces a wider choice for signal matching.

Figure 8 shows results obtained with the target-independent burial-depth calculation method. It can be seen that the method is not perfect and errors can reach 25mm for the 11-mm ball. Figure 9 plots the discrimination values for the five targets at different burial depths. This data can be used to actually discriminate targets. Given a reasonable threshold as indicated in shaded color, we can safely discriminate the 3- and 5-mm ball, and the aluminum cylinder. The 11-mm ball, which apparently presents characteristics most similar to the ITOP, can also be safely discriminated up to a depth of 71mm. At deeper depths, it is probably safer to consider it as an ITOP.

In-field Experiments and Results

The Tokyo Institute of Technology developed a mine-searching robot that autonomously scans a 3-square-meter area with any attached sensor.[6, 7, 8] Once in position along the minefield borderline, the robot uses a stereo vision camera to acquire topographical terrain information

Gryphon scanning over a test-minefield in Cambodia.

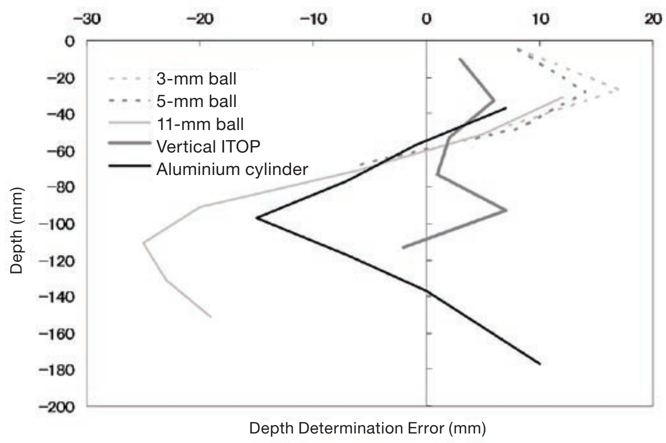


Figure 8: Depth determination errors for the target-independent burial depth calculation method.

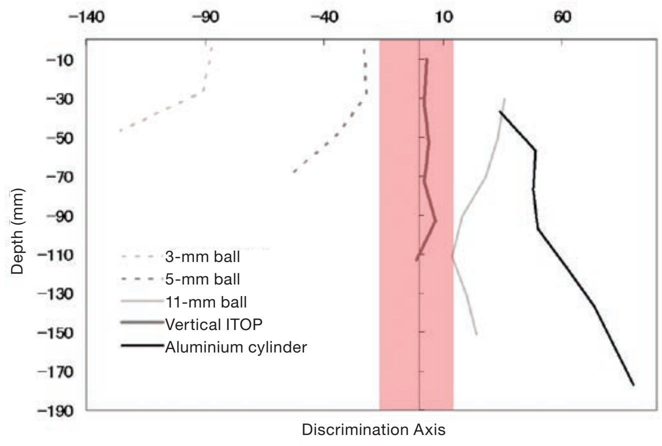


Figure 9: Discrimination capability; the discrimination axis indicates the depth difference of the two calculation methods.

and then uses that map to generate necessary movement sequences to scan the terrain at a vertical distance of 20 mm. The manipulator's five degrees of freedom allow it to adaptively scan above uneven terrain. The robot, called Gryphon (see image above),[9] underwent extensive field tests in Japan[10] and Croatia.[11] From November 2006 to January 2007 it also took part in field trials in Cambodia—two Gryphons, each with a different sensor configuration (MD/MD-ground-penetrating radar), performed tests on prepared minefields during a combined 150 hours of semi-autonomous operation. At the same time, one Gryphon performed discrimination experiments on sand, laterite and clay soil types.

Experiment set-up. In-field data acquisition was achieved using Gryphon. Instead of moving the target over the MD as in laboratory tests, the target was kept fixed while the MD scanned over it with a data density of 40,000 points/sq m. Acquired data was later transformed to obtain images of moving targets for a fixed MD. Each time, a 15-mm diameter and 300-mm long plastic tube was vertically embedded into the soil, allowing a flexible target and target-depth change (see image below). The tube and air gap had negligible influence on the MD readings. The scanning height to the ground was kept at 20mm.

An MD reset procedure preceded each test. At first, each reset was also followed by a soil-compensation procedure, which was not beneficial; it even reduced sensitivity non-systematically, so that data was hardly usable. All measurements were then repeated without a soil-compensation procedure. Recorded data was then modified by adding an offset value in order to have negative and positive values with same amplitudes. This procedure can be seen as an *a posteriori* soil-compensation procedure. An in-sand acquired ITOP sensitivity profile and mask were used throughout the experiments.

Results. Only input images with clear pattern and little noise levels were used in the discrimination experiment. Figure 10 (next page) shows an example of which image is tolerated and which is not: while Figure 10a is still acceptable, Figures 10b and 10c show definitely no regular pattern anymore and are therefore rejected.

The target-dependent burial-depth calculation method produced precise depths for the ITOP, with a maximum error of 3mm, irrespective of the soil type. The other targets showed consistent and regular values as for the in-laboratory measurements. The target-independent

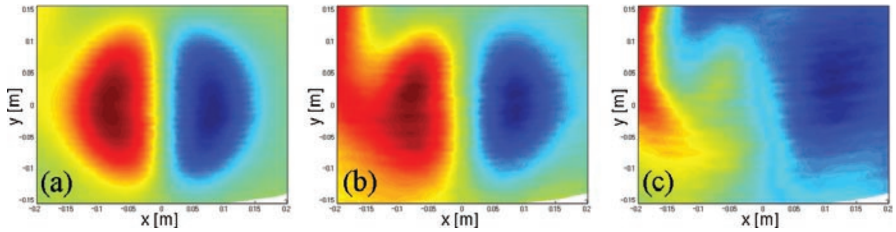
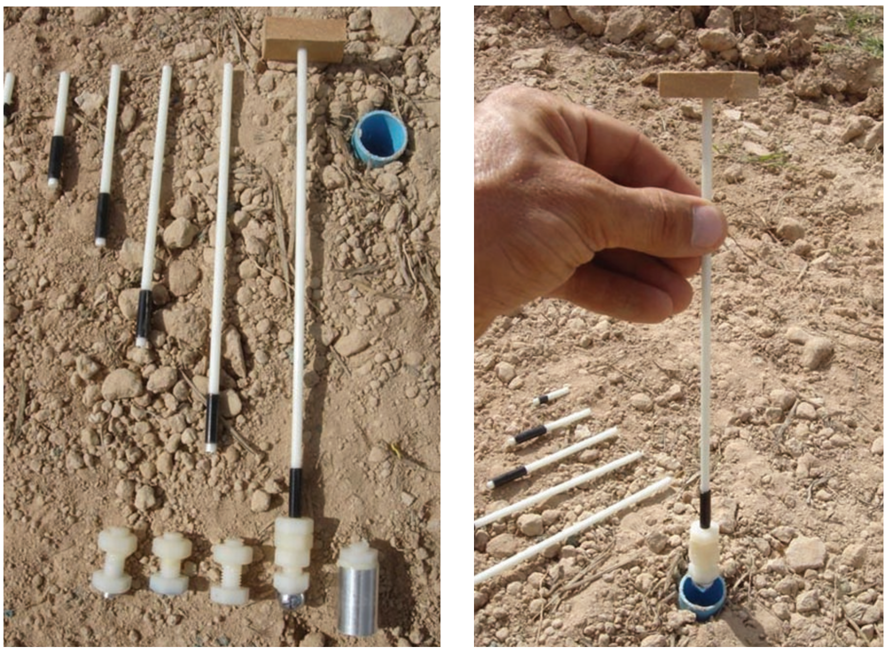


Figure 10: In-clay input images of 5-mm ball at depths of (a) 60mm, (b) 90mm and (c) 120mm.



Target and target-depth set-up and insertion into the soil.

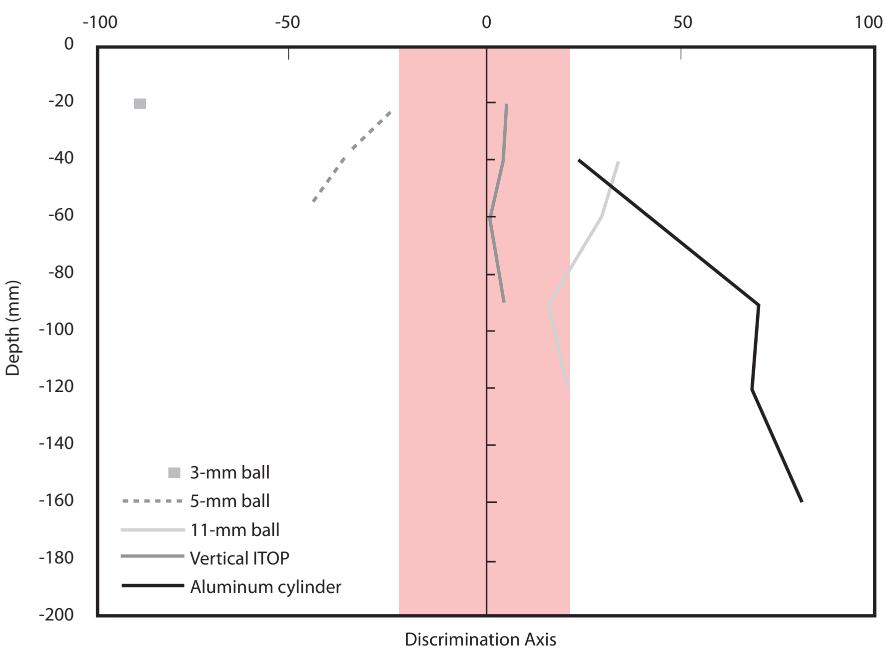


Figure 11: In-sand discrimination capability; the discrimination axis indicates the depth difference of the two calculation methods.

burial-depth calculation method, on the other hand, produced less precise depths, with errors reaching up to 25mm for the 11-mm ball. The results, however, are consistent with data obtained in-laboratory.

Figure 11 (left), Figure 12 and Figure 13 (see both next page) show the discrimination graphs for the in-sand, in-laterite and in-clay measurements respectively. Having used an in-sand ITOP sensitivity profile and mask, there is little surprise that the discrimination looks fine for the in-sand buried targets. However, there is only little degradation of the discrimination capabilities of the method when looking at the in-laterite and in-clay buried targets. It seems that the soil type has only little effect with the considered targets. The clay-soil, however, sees a quick appearance of a static noise pattern that hides the signal of small targets, thus the depth at which the method could be applied on clay soil was less significant than for the sand or laterite soil. In general, in-soil measurements are more affected by noise compared to in-laboratory measurements, but these measurements still allow us to obtain good discrimination results.

Discussion

The experiments showed clear discrimination capabilities. It must be mentioned that in order to discriminate for a specific landmine type, one has to be sure that there are no additional landmine types present in the searched minefield. The discrimination method can only be applied with restrictions in areas where several landmine types are present (e.g., by using one distinct sensitivity profile/mask for each landmine type). Also, the cases in which several targets lie within a short distance, say a few centimeters, or when the targets produce a very different image (flat or long objects), have to be carefully examined. Areas hit by cluster strikes could also benefit from the presented method since the type, load and footprint of munitions would be known beforehand.

The weakness of the method is the target-independent burial-depth calculation that presents relatively high errors compared to the target-dependent burial-depth calculation; performing several identical scans would probably help acquire better data for profile/mask generation and/or obtaining more precise input images. This in turn would increase the precision of burial-depth calculation.

The discrimination method can be used with other types of statically operating MDs, but there are restrictions regarding depth. MDs using a single circular coil are limited to a few centimeters only, the reason being that the sensitivity mask will not change any more from that depth (Figures 14c and 14d are the same). Non-circular coils will have their sensitivity mask change over deeper depths (Figures 14g and 14h are slightly different).

Interesting possibilities to explore would be to tune the hardware in order to obtain more precise target-independent burial-depth calculations by adjusting the position of the MD coils or by electronically "steering" the MD's electromagnetic field. The latter could also lead to reduced scanning times during which physical scanning with the MD would only be performed along the MD's y-axis (the x-axis being covered through the electromagnetic field sweeping).

The scanning motion and image acquisition are currently performed by Gryphon, but any appropriate MD equipped with a position-acquisition device (e.g., tracking camera) can produce a cheap and lightweight alternative.

Conclusion

We presented two depth-calculation methods that allow discrimination of metallic targets from landmines to a certain extent: the discrimination algorithm applies to a class of relatively small and relatively isotropic targets and is ideally suited for discrimination of a large range of targets typically contained in anti-personnel landmines. At the same time, knowing the target's burial depth can increase safety by allowing for better target pinpointing during a prodding operation.

Experimental data shows good discrimination capabilities and relatively precise burial-depth determination—4mm when the target could be identified, 25mm otherwise. The discrimination algorithm prohibits blind application; input-images not presenting clear and **standard** patterns or with high noise levels should be discarded. Future improvements will look at the possibility to automatically evaluate an input image according to certain applicability criteria.

Soil type influences MD reading but does not seem to have a direct effect on the applicability of the discrimination method. At the current stage, the method cannot yet be used to discriminate landmines with a 100-percent certainty. It, however, can add to the deminer's safety by allowing for an adapted and more informed behavior when prodding the soil.

See Endnotes, page 114

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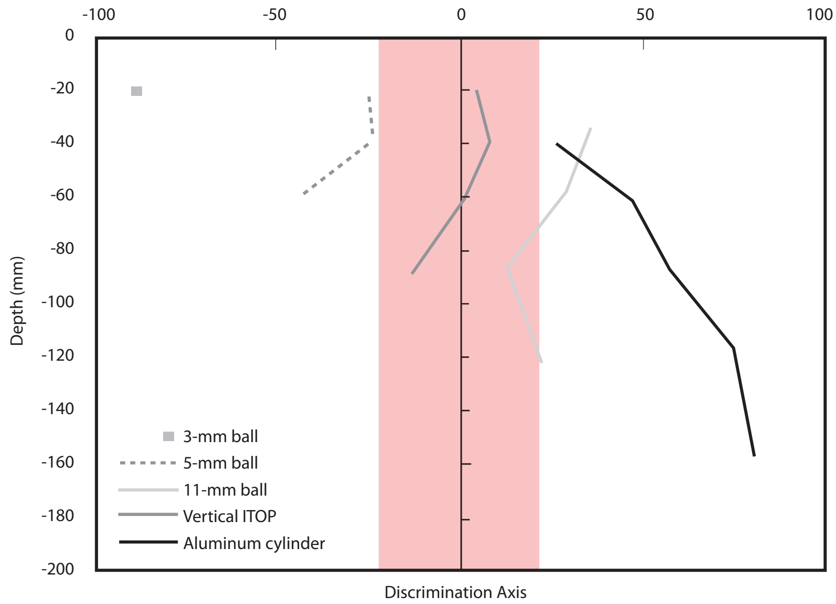

Figure 12: In-laterite discrimination capability; the discrimination axis indicates the depth difference of the two calculation methods.

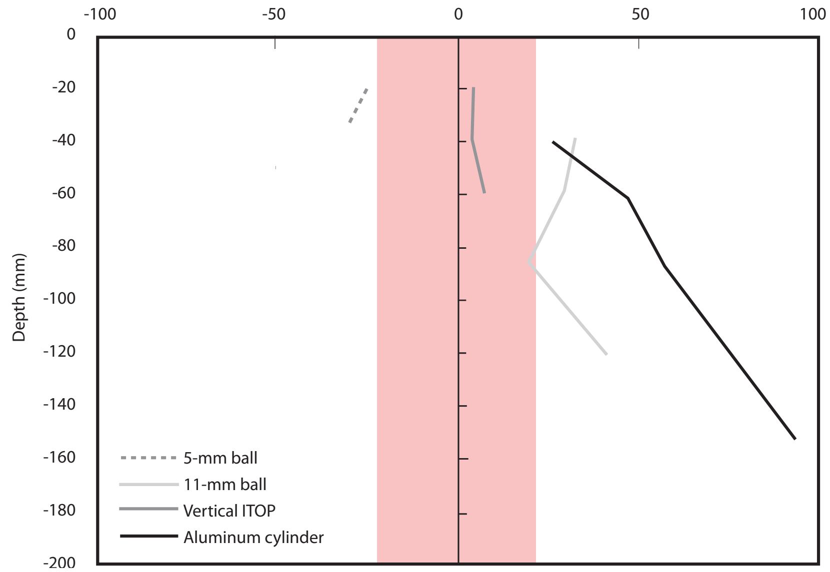

Figure 13: In-clay discrimination capability; the discrimination axis indicates the depth difference of the two calculation methods. The 3-mm ball image at 20 mm depth is already too noisy to be included in the graph.

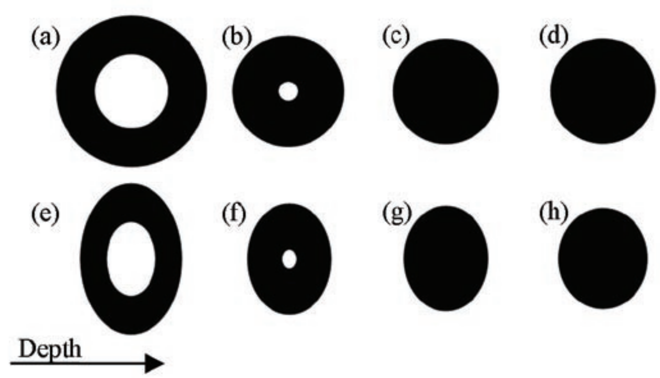

Figure 14: Cut through the sensitivity mask of single detection coil MD for the circular coil (a–d) and for the elliptical coil (e–h).

Marc Freese is a Research Associate in the Department of Mechanical and Aerospace Engineering at the Tokyo Institute of Technology. His current research activities include the development of demining robots and the development of robot simulation software.

Marc Freese
MayFlower Members Ville Rm 914
104-9 Guro-dong, Guro-Gu
152-051 Seoul / Korea
Tel: +81-3-5734-2648
Fax: +81-3-5734-2648
E-mail: freese.m.aa@m.titech.ac.jp

Edwardo F. Fukushima is an Associate Professor in the Department of Mechanical and Aerospace Engineering at the Tokyo Institute of Technology. His current research activities include the development of demining robots, design of controllers for intelligent robots, and development of new brushless motors and drives.

Edwardo F. Fukushima, Dr. Eng.
Associate Professor
Dept. of Mechanical and
Aerospace Engineering Graduate
School of Science and Engineering
Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku
Tokyo 152-8552 / Japan
Tel/Fax: +81 3 5734 3175
E-mail: fukusima@mes.titech.ac.jp

Shigeo Hirose is a Professor in the Department of Mechanical and Aerospace Engineering at the Tokyo Institute of Technology. He is also an Honorary Professor at the Shengyang Institute of Technology, and Fellow of JSME and IEEE. He has been awarded more than 20 prizes in his career, and is actively engaged in creative design of robotic systems.

Shigeo Hirose
Professor
Tokyo Institute of Technology
E-mail: hirose@mes.titech.ac.jp

News Brief

Nepal Expresses Commitment to Becoming Mine Free

Members of the Nepalese Constituent Assembly gathered in early August with representatives from national and international nongovernmental organizations, civil-society groups, and security forces to express a commitment toward building a mine-free Nepal.

The declaration they made, entitled "Mine Action and the Ottawa Treaty," focuses on providing holistic victim assistance (through financial, material and other resources) and remediating national contamination from landmines and other explosive remnants of war. The declaration builds on anti-landmine efforts already active in Nepal; with support from the Campaign to Ban Landmines–Nepal, the Nepalese Minister for Peace and Reconstruction has signed a letter of support for banning landmines. Demining activities are underway, but observers note a disappointing lack of progress. Organizers hope this newest declaration will lead Nepal to become a State Party to the Ottawa Convention.

Mine contamination and the use of improvised explosive devices have been prevalent in Nepal as part of that country's prolonged internal struggles. Since the cessation of hostilities in 2006, demining activities have not progressed quickly, and much of the country remains affected by mines and other ERW. The cease-fire agreement has held, making the formation of a national mine-action authority possible; however, the lack of manpower and demining capacity (both financial and technical) has hampered efforts. Beyond possible accession to the Ottawa Convention, the new declaration could increase support for mine action in-country, as well as internationally.