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Test and Evaluation of Japanese GPR-based AP Mine Detection Systems Mounted on Robotic Vehicles

This article introduces Japanese activities regarding a project, “Research and Development of Sensing Technology, Access and Control Technology to Support Humanitarian Demining of AP Mines.” This project, which includes the research of six teams from academia and industry, has been funded by the Japan Science and Technology Agency (JST) under the auspices of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The developed systems are equipped with both ground-penetrating radar and a metal detector, and they are designed to make no explicit alarm and to leave decision-making of detection using subsurface images to the operators. To evaluate these kinds of systems, a series of trials was conducted in Japan from 8 February to 11 March 2005.

A t current clearance speed, it will take more than 100 years to remove all the landmines that remain in the world. Consequently, Japan is developing more efficient and safer humanitarian demining technologies. This article introduces Japanese robotic sensor systems that provide deminers with clear subsurface images via ground-penetrating radar in combination with metal detectors (GPR-MD).

Experiment Overview: Background
To reconstruct clear images, highly accurate sensor-positioning systems, as well as sensing technology itself, are indispensable because one of the most important pieces of information for signal processing is sensor position, where the sensor acquires a series of data for GPR-MD.

There are many kinds of anti-personnel landmines, which can be laid by humans or scattered by airplanes, and mined areas are not limited to plains but also marshes, canals, steep hillsides, seashores, deserts, mountains and forests. For such rough terrain, robotic systems must have sensor heads that can scan the ground as closely as possible but never touch it as well-trained deminers do. Metal detectors, which are a kind of an electromagnetic induction (EMI) sensor, have the possible detection distance of about 15 centimeters for minimum-metal landmines. For these metal detectors, it is a challenge for sensor systems to access minefields and manipulate the sensor head in severe environments in order to stay as close to the ground as possible. Thus, Japanese advanced robotics and sensor engineering have been fused to create novel detectors.

Japan started preparation for this kind of research and development in March 1997, when the Tokyo Conference on Anti-personnel Landmines was held. At this conference, participants underscored a comprehensive discussion to strengthen international efforts toward addressing the problems of AP landmines, especially landmine clearance by the United Nations and other organizations; development of new technology for mine detection and removal; and assistance to victims. In December 1997, Keizo Obuchi, then Minister for Foreign Affairs of Japan, signed the Ottawa Convention, and the ultimate goal of zero victims was postponed. Since August 2002, the Japanese have undertaken preparations to start humanitarian-demining R&D.

Japanese R&D of Anti-personnel Landmine Detection System
With strong expectations from the world community for Japanese contributions in this area, the Ministry of Education, Culture, Sports, Science and Technology established the Committee of Experts on Humanitarian Demining Technology in January 2002, believing in the importance of tackling the technological development of AP landmine detection using advanced Japanese technology. The Committee’s findings were presented to MEXT in the report, “Promoting R&D for Humanitarian Demining Technology.” Based on this report, the Japan Science and Technology Agency announced a call for proposals for R&D projects in humanitarian-demining technology. Out of the 82 proposals, 12 projects were selected, and an R&D project named “Research and Development of Sensing Technology, Access and Control Technology to Support Humanitarian Demining of Anti-personnel Mines” started in October 2002.

The JST project is essentially divided into a short-term R&D project and a medium-term one. Because of the urgent need for this technology, the short-term R&D project is expected to have prototypes in field trials within three years. The JST medium-term R&D project is on a five-year schedule. The goal is to develop sensing technologies that can detect the explosive itself, in the range of about 30 to 100 grams.

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Figure 1a: Detection images from stepped-frequency GPR. Horizontal slices showing two targets at a five-centimeter depth (left) and a target at a 25-centimeter depth (right).

Short-term R&D project. The objectives of the short-term R&D project are to develop sensing technology that can safely and efficiently detect AP landmines based on the physical differences between landmines and soil, and to develop access devices and manipulation technology that carry sensors into minefields and allow them to scan the ground precisely. More specifically, the goal is to develop small, self-mounted GPR-MD dual-sensor systems that make no explicit alarm and provide operators with clear CT images. This feature discriminates the systems from conventional GPR-MD dual sensors that are based on alarm tones.

In the short-term project, four sensors and three robotic vehicles have been developed. One of these is the Mine Hunter Vehicle. The vehicle itself and the manipulator have been developed by a research team of Professor Kenzo Nonami at Chiba University.6 The MHV can interchangeably mount two GPR sensors in addition to a commercial, off-the-shelf metal detector. One sensor is a stepped-frequency GPR developed by Professor Motomori Sato at Tohoku University,7 hereinafter referred to as MHV #1. Stepped-frequency radar determines distance to a target by measuring the time delay of a pulse, which is a time domain approximation derived from the frequency response of a combination of stepped-frequency signals via inverse fast Fourier transform (IFFT). The major advantage of the stepped-frequency method is that the spectrum bandwidth can be easily tuned to fit an optimum value according to environmental conditions such as soil moisture. The other sensor is an impulse GPR developed by Professor Shigeo Hirose’s team at the Tokyo Institute of Technology. The GPR is a buggy system, which can be remotely controlled to access minefields.8 The manipulator mounted on the buggy has been designed to cancel reaction force induced by scanning.9 The sensor is a GPR-MD dual sensor named the Advanced Landmine Imaging System (ALIS), and it can also be used as a handheld detector.10 ALIS was developed by Professor Sato’s team and underwent a field trial in Afghanistan in December 2004. Medium-term R&D project. Professor Hiroki Izuka’s group at Osaka University is developing a nuclear quadrupole-resonance detector.11 In the analysis, a radio-frequency electromagnet is first excited and emits nuclear spin “N” of in-transit magnetic wave detector, such as an induction coil, detects subsurface NQR signals from the “N” of any intended target exists, and the resonance frequency of the signal is unique for each explosive material. Thus explosive signals can be identified.

Two research teams on the project are trying to develop detectors based on the neutron analysis identifying explosives through backscattering of neutrons and detection of specific energy gamma rays from capture on hydrogen and nitrogen atoms of explosives. Professor Kiyoshi Yoshikawa’s group from Kyoritsu University has prototyped an extremely compact neutron source based on an inertial-electrostatic confinement fusion device 20 centimeters in diameter.12 Professor Tetsuo Iguchi’s group of Nagoya University has prototyped another neutron source, which is an improved Cockcroft-Walton-type accelerator neutron source using a deuterium-deuterium (DD) fusion reactor. They have also developed a prototype of a multi-Compton gamma camera, which estimates the incoming direction of 10 MeV gamma-rays produced from the neutron of the explosive (Figure 2).13 The medium-term R&D project is expected to have prototypes in field trials within five years, namely in 2007, in combination with one of the prototypes of MHV, AMS or GPR.

Figure 1b: Detection images from stepped-frequency GPR. Three-dimensional image of three targets in the horizontal slices.

The sensor system scans the ground, being carried by a low-reaction force manipulation frame that has four wheels on the legs to safely land on it on minefields. The manipulation frame is attached to the top of a boom of a crane vehicle developed by Mr. Tomohiro Hata of TADANO Ltd. The vehicle has a 20-meter reach for a 200-kilogram payload with a positioning accuracy of 15 centimeters. These elements have been integrated into the Advanced Mine Sweeper (AMS), which can adapt to various geographical environments.14 Professor Sligo Himre’s team at the Tokyo Institute of Technology developed the Grenph buggy system, which can be remotely controlled to access minefields.15 The manipulator mounted on the buggy has been designed to cancel reaction force induced by scanning. The sensor is a GPR-MD dual sensor named the Advanced Landmine Imaging System (ALIS), and it can also be used as a handheld detector.16 ALIS was developed by Professor Sato’s team and underwent a field trial in Afghanistan in December 2004.

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4. The testee reports the following data for every detected anomaly:
   - Coordinates of the detected target
   - Depth of the detected target
   - Confidence rating defined in Table 5 and the final decision whether or not to declare the anomaly as a landmine surrogate
5. The tester determines whether the declared anomaly can be considered to be from the intended target, 27 that is, within a detection halo, the radius of which is half of the target diameter plus 10 centimeters.
6. Finally, the tester classifies the reported data into four categories:
   - True positive: The testee declared it as a target and this is true.
   - False positive: The testee declared it as a target and this is not true. This is a false alarm.
   - True negative: The testee declared it as a fragment, clutter or noise and this is true.
   - False negative: The testee declared it as a fragment, clutter or noise and this is not true. This is missing a target.
Completing the tests from lanes 1 through 6 means that the testee finished all 24 experimental runs of Experiments 1 and 2 described in Tables 3 and 4.

The most important thing is to practically use these technologies to improve landmine-detection efficiency and reduce minefields. To do so, the mine-detection systems must be robust, simple and highly cost-effective. The Japanese domestic trial is the first step.

**Test and Evaluation Results**

The following is the data analysis and evaluation of test results for anti-personnel landmine detection systems using ground-penetrating radar mounted on robotic vehicles for humanitarian demining.17,18

<table>
<thead>
<tr>
<th>Factor</th>
<th>Number of Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Assigned column</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Target type</td>
<td>M14, PWN2, TYPE72, TYPE2-S</td>
<td>4.8,12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Target depth</td>
<td>0cm, 10cm, 20cm, 30cm</td>
<td>5,10,15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Soil condition</td>
<td>Flat, Wet, Snow</td>
<td>7.5,14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: Target angle</td>
<td>Vertical, Level</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Factors A to D and the levels for Experiment 1.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Number of Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Assigned column</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Distance to adjacent target</td>
<td>&gt;50cm, 50cm</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Target depth</td>
<td>0cm, 10cm, 20cm, 30cm</td>
<td>2,4,6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Soil condition</td>
<td>Flat</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Factors A to C and the levels for Experiment 2.

**Benchmarking.** To compare performance of the GPR-EMI dual sensor system with that of existing metal detectors, a benchmarking trial was conducted. Namely, a tester who knew the exact positions of targets checked if any metal-detector response occurred just above every buried target. The result of this test shows the best performance of the metal detectors used.

**Test procedures.** Testees took blind tests for each lane following the procedure described below:
1. Before the test starts, the tester records temperature, relative humidity and volumetric water content that is measured by time domain reflectometry (TDR).
2. The testee then consistently works using a sensor system according to the experimental design presented in Tables 3 and 4.
3. After the work finishes, the tester records temperature, relative humidity and volumetric water content measured by TDR.
4. The test results showed that combining GPR with metal detectors can improve probability of detection for targets around a depth of 20 centimeters, where it is difficult to detect targets by using only a metal detector. It has also been learned that positioning control must be improved in scanning the ground with a sensor head, which is key to making the best use of metal detectors mounted on vehicles. Lessons learned have been reflected in further improvement of the processes. In the following sections, data analysis methods and evaluation results are described.

**Data analysis.** According to the experimental design proposed above, data from eight testees (two each from every system) have been acquired. The comprehensive results of probability of detection (PD) are shown in Tables 6 and 7. PD results for Experiments 1 and 2. The systems named are anonymous and described as Device 1, Device 2, and Device 3.

**Table 6: PD of eight testees of Experiment 1. Highlighted data of four testees are analyzed as shown in Figure 13.**
Now, for example, a linear model for the probability of detection $P_D$ can be expressed as:

$$P_D = \frac{1}{2} \left( 1 + \frac{1}{2} (\alpha + \beta) \right)$$

Equation 6

For the ANOVA, four means of squares (variances) are calculated as follows:

$$V_A = \frac{S_A}{\frac{1}{2} (\alpha + \beta)}$$

Equation 7

$$V_B = \frac{S_B}{\frac{1}{2} (\alpha + \beta)}$$

Equation 8

$$V_C = \frac{S_C}{\frac{1}{2} (\alpha + \beta)}$$

Equation 9

$$V_{error} = \frac{S_{error}}{\frac{1}{2} (\alpha + \beta)}$$

Equation 10

where $\alpha$ and $\beta$ are the degrees of freedom of factors $A$ and $B$.

By comparing the variances due to levels of each factor $A$, $B$, and $C$ with the variance due to measurement error $V_{error}$ (using F-test), the significance of the differences between levels is tested. In this test, the null hypothesis is that the main effects of levels for a factor are all equal (i.e., there is no difference in influences of levels for the factor on PD). The computed F-statistic in Table 9 follows an F-distribution with corresponding degrees of freedom under the assumption that variances of PD have homogeneity. Therefore, the significance of F can be determined in the way by using the table of F. If the computed value of F is larger than the tabulated value, the null hypothesis is rejected. This means that at least one pair of main effects is significantly different.

As described above, detection results reported by ten testees are classified into four categories: true positive, false positive, true negative, and false negative. However, the classification based on tenee's discrimination threshold is a one-sided view, and the number of true positives and the number of false positives changes as the threshold is varied. An ROC curve shows the relationship between the true positive and false positive for a variety of different thresholds, thus helping the determination of an optimal threshold as well as the comparison of sensor performance.

To plot an ROC curve, two histograms, which are measured on an interval scale in the confidence rating reported by the tenee, are needed. One is from signals of intended target that consist of true positives and false negatives, and the other is from signals of fragments, clusters, or noise (i.e., true negatives and false positives). According to the histograms, the ratio of true positive (i.e., probability of detection) is plotted as a function of the ratio of false positive at every confidence level.

The 95-percent confidence limit of each main effect is experimentally derived by using $V_{error}$ the mean of squares due to error. For example, the 95-percent confidence interval of $S_{error}$ is given by:

$$\frac{1}{2} \frac{V_{error}}{\chi^2_{0.05}}$$

Equation 11

where $\chi^2_{0.05}$ is the total number of experiments (the number of experimental runs multiplied by repetitions), and $S_{error}^{25\text{th}}$ is the quintile of the $\chi^2$-distribution for probability 95 percent with $\frac{1}{2}$ degrees of freedom.

Receiver operating characteristic curve. It has been 30 years since radiographic applications of ROC curves were reported and it is well-known that analysis based on ROC curves is suitable for subjective evaluation of imaging equipment. In the test and evaluation here, ROC curves were also used to evaluate sensor effectiveness in terms of both PD and false-alarm rate.
rating (threshold). As shown in Figure 6, if a sensor functions well, a histogram of targets (solid line) is distributed apart from that of noise (dotted line), and the resulting ROC curve climbs rapidly toward the upper left-hand corner of the graph as shown by the solid line in Figure 7. On the other hand, if another sensor gives a histogram of targets that is indistinguishable from that of noise, the resulting ROC curve gets closer to a diagonal line as shown by the dashed line in Figure 7. This means the discriminating power decreases. Once ROC curves are obtained, there are many methods to test the difference between ROC curves.32

In the experiment, the number of true positives is controlled, but the number of false positives depends on how many false alarms are reported by the testee. Therefore, all the histograms discussed here are normalized by dividing frequencies by the total number of the population.

Experimental Results

Figure 8 shows the ground truth of the lane 2, and Figures 9 and 10 shows subsurface images from a sensor system. In this case, it has been shown that a metal detector can clearly image seven pairs of Type72 surrogates buried flush (Figure 9), and that a GPR sensor can display seven PMN2 surrogates at a depth of 20 centimeters (8 inches) (Figure 10), where the metal detector was not able to get any signal. Based on these kinds of images, testees have derived their detection results, and the next section discusses the experimental results.

Probability of detection. The number of testees is eight, the breakdown of which is two from MHV with a step-frequency GPR-MD (MHV #1), two from MHV with a pulse GPR-MD (MHV #2), two from the Advanced Mine Sweeper with a step-frequency GPR-MD, and two from Gryphon with a pulse GPR-MD. The eight sets of data were analyzed by ANOVA to see the effects of factors. Note that the order of the systems is not consistent with devices 1–4 to keep anonymity.

Tables 10 and 11 show ANOVA results for Experiments 1 and 2, respectively, and Figures 11 and 12 show plots of factor effects (i.e., main effects added to the mean μ with 95-percent confidence intervals derived in the same way as Equation 11). In Tables 10 and 11, factors, the null hypothesis of which has been rejected at the level of significance of 0.05 (0.0), are indicated by * (0.05) ** (0.01). For those factors, there have been significant differences in PD between the levels, and it can be said that it is meaningful to discuss how those factors influence PD and that the test lanes were well-designed to evaluate the sensor systems. It has been shown that there is a strong dependence of PD on target depth and that the developed systems still have problems for rough and uneven ground surface (Figures 11 and 12). Regarding factor A of Experiment 2, distance to adjacent target, the ANOVA showed that there was no significant difference in PD between a pair of Type72-S surrogates at a 35-centimeter distance and the other independent Type72-S surrogates.

Averages of PD of four testees, that is, one each from every system, are plotted in Figures 13 and 14, compared with the benchmarking results using only a metal detector. Confidence limits can be calculated the way that K. M. Simonson discusses in the Sandia Report33 as the number of population for each level is derived from Tables 10 and 11 above. The results showed that the PD for targets deeper than 10 centimeters can be improved by combining GPR with MD. On the other hand, as also shown in Figures 13 and 14, some of the GPR-MD results in shallow levels were worse than those of metal detectors. This is because sensor height above the ground, which is controlled by manipulators, is higher than that of manual scanning of metal detectors, and this is considered to be improved by modifying the manipulation algorithm of a robotic part.

Lessons learned. Through the test and evaluation process, many lessons have been learned, some of which are listed below:

• The provided calibration area should have contained landmine surrogates for all levels of factors. Coaching a typical image for each level would much improve the detection rate.

• In some cases (for example, Site Testee 7), high PDs have been accompanied by high false-alarm rates around 30 times/square meter, and it was also proven that confirming the source of false alarms for GPR is much more difficult than those of metal detectors (i.e., metal fragments). Therefore, another performance index to penalize those GPR false alarms will be needed.

• PD in deep levels of 20–30 centimeters can be improved by combining GPR with MDs.

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3. Published by JMU Scholarly Commons, 2006.
The authors examine the various equipment and technologies that allow further effectiveness in demining achievements. Recent developments in demining tools allow for greater protection of deminers, in addition to improved search results. With technological advancements such as the Survivable Demining Tractor and Tools and the Mine-Clearing Survivable Vehicle, the authors express hope for demining centers worldwide.

by Thinh Nguyen and Charles Chichester [U.S. Humanitarian Demining Research and Development Program]

The international demining community continues to seek reliable, efficient, and cost-effective mine- and vegetation-clearance equipment to assist in demining operations. The U.S. Humanitarian Demining Research and Development Program is responding to this need by focusing much of its effort on developing, demonstrating, and validating technologies that help the demining community clear mines and vegetation faster, safer, and more efficiently.

One of the ways in which the Humanitarian Demining R&D Program brings effective, reliable, yet affordable technologies to the field is through the adaptation of commercial off-the-shelf (COTS) equipment. In particular, one of its most successful strategies is using a COTS platform and adding tool attachments to create a multi-functioning vehicle. Through past efforts, the HD R&D Program has proven the concept that using a single prime mover with a toolkit comprising a well-thought-out selection of tools can reliably and rapidly perform the demining tasks of land preparation, mine removal, and area reduction and reclamation, leaving an area ready for quality-assurance proofing. Two such systems currently in use by demining programs are the Survivable Demining Tractor and Tools and the Mine-Clearing Survivable Vehicle (aka Mantis). Both systems use COTS platforms and a variety of attachment tools to perform multiple demining roles.

The Survivable Demining Tractor and Tools

The SNDT was first developed in 1997 and is one of the earliest successes of the HD R&D Program. The system uses a modified commercial New Holland 160-90 farm tractor fitted with armor plating, optional steel wheels and a variety of specialized implements used to clear heavily vegetated areas and support various demining operations from area preparation to quality assurance. Attachments include rollers, magnets, slasher, forestry tippers, rakes, hedge trimmers, sifters, light and heavy cultivators, large and small grabbers, pallet forks, and light and heavy tree-pullers. The system mechanically assists the manual demining process by providing deminers numeous tools and an armored platform from which to perform the most hazardous tasks. The versatility of the system allows deminers to work more efficiently.

The SNDT is currently in use by the Thailand Mine Action Center to clear vegetation and prepare the land for manual demining. From 2001 through 2005, the SNDT cleared over 8,863,350 square meters of mine threatened areas.

Table 12: False-alarm rate (1/square meter) of eight testees for each lane.

<table>
<thead>
<tr>
<th>Lane #</th>
<th>Device #1</th>
<th>Device #2</th>
<th>Device #3</th>
<th>Device #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.3</td>
<td>12.4</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>8.5</td>
<td>6.6</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>16.4</td>
<td>47.0</td>
<td>4.2</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>15.4</td>
<td>16.7</td>
<td>4.2</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>8.5</td>
<td>6.6</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>9.9</td>
<td>19.7</td>
<td>4.2</td>
<td>1.3</td>
</tr>
<tr>
<td>7</td>
<td>16.0</td>
<td>9.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>16.0</td>
<td>9.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Figure 15a: ROC curve for lane 2 (testee 7). The total number of negatives (fragments, clutters or noise) is shown.

Figure 15b: ROC curve for lane 2 (testee 7). The total number of negatives (fragments, clutters or noise) is shown.

Figure 15c: ROC curve for lane 4 (testee 3). The total number of negatives (fragments, clutters or noise) is shown.

Figure 15d: ROC curve for lane 4 (testee 3). The total number of negatives (fragments, clutters or noise) is shown.