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초빙논문

GPR Development for Landmine Detection
지뢰탐지를 위한 GPR 시스템의 개발

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Abstract : Under the research project supported by Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), we have conducted the development of GPR systems for landmine detection. Until 2005, we have finished development of two prototype GPR systems, namely ALIS (Advanced Landmine Imaging System) and SAR-GPR (Synthetic Aperture Radar – Ground Penetrating Radar). ALIS is a novel landmine detection sensor system combined with a metal detector and GPR. This is a hand-held equipment, which has a sensor position tracking system, and can visualize the sensor output in real time. In order to achieve the sensor tracking system, ALIS needs only one CCD camera attached on the sensor handle. The CCD image is superimposed with the GPR and metal detector signal, and the detection and identification of buried targets is quite easy and reliable. Field evaluation test of ALIS was conducted in December 2004 in Afghanistan, and we demonstrated that it can detect buried antipersonnel landmines, and can also discriminate metal fragments from landmines. SAR-GPR (Synthetic Aperture Radar – Ground Penetrating Radar) is a machine mounted sensor system composed of a GPR and a metal detector. The GPR employs an array antenna for advanced signal processing for better subsurface imaging. SAR-GPR combined with synthetic aperture radar algorithm, can suppress clutter and can image buried objects in strongly inhomogeneous material. SAR-GPR is a stepped frequency radar system, whose RF component is a newly developed compact vector network analyzers. The size of the system is 30 cm × 30 cm × 30 cm, composed from six Vivaldi antennas and three vector network analyzers. The weight of the system is 17 kg, and it can be mounted on a robotic arm on a small unmanned vehicle. The field test of this system was carried out in March 2005 in Japan.

Keywords : Land mine detection, Hand-held sensor, Metal Detector, GPR, Position tracker, visualization, ALIS, SAR-GPR, Synthetic Aperture Radar, SAR, Migration

요 약 : 일본 문부과학성의 연구 지원하에 지뢰 탐지를 위한 GPR 시스템 개발에 관한 연구를 수행하였다. 2005 년도까지 두 종류의 새로운 지뢰탐지 GPR 시스템 원형의 개발을 완성하였으며 이를 ALIS (Advanced Landmine Imaging System)와 SAR-GPR (Synthetic Aperture Radar – Ground Penetrating Radar)이라고 명명하였다. ALIS는 금속탐지기와 GPR을 결합한 새로운 형태의 휴대용 지뢰탐지 시스템이다. 센서의 위치를 실시간으로 추적하는 시스템을 장착하여 센서에 감지된 신호를 실시간으로 영상화할 수 있도록 하였으며, 센서 위치의 추적은 센서의 손잡이에 장착한 CCD 카메라만을 이용하여 가능하도록 고안하였다. 그리고 GPR과 금속탐지기 신호를 CCD 카메라에 포착된 영상에 중첩하여 동시에 영상화하도록 설계하였기 때문에 매설된 탐지 목적물을 용이하게 그리고 신뢰할 만한 수준으로 탐지하고 구별할 수 있다. 2004 년 12월에 아프가니스탄에서 ALIS의 현장 검증 실험을 수행하였으며, 이를 통해 이 연구에서 개발한 시스템을 이용하여 매설된 대인지뢰를 탐지할 수 있을 뿐만 아니라 대인지뢰와 금속 파편의 구분 또한 가능함을 보였다. SAR-GPR은 이동 로보트에 장착한 지뢰탐지 시스템으로 GPR과 금속탐지기 센서로 구성된다. 다수의 송, 수신 안테나로 구성된 안테나 배열을 채택하여 개선된 신호처리 기법의 적용을 가능하며, 이를 통해 좀 더 나은 지하 영상의 획득이 가능하다. SAR-GPR에 합성개구 레이다 알고리듬을 채용함으로써 원하지 않는 클러터(clutter) 신호를 억제하고 불균질도가 높은 매질 내부에 매설된 목적물을 영상화할 수 있다. SAR-GPR은 새로이 개발한 휴대용 벡터 네트워크 분석기를 이용한 스텝 주파수 레이다 시스템(stepped frequency radar system)으로 6 개의 Vivaldi 안테나와 3 개의 벡터 네트워크 분석기로 구성된다. SAR-GPR의 크기는 30 cm × 30 cm × 30 cm, 중량은 17 kg 정도이며 소형 무인 차량의 로보트 팔에 장착된다. 이 시스템의 현장 적용 실험은 2005 년 3 월 일본에서 성공적으로 실시된 바 있다.

주요어 : 지뢰탐지, 휴대용 탐지기, 금속탐지기, GPR, 위치추적 장치, 가시화, ALIS, SAR-GPR, 합성개구 레이더, 구조보정

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Introduction

Humanitarian Demining is gathering interest all over the world. Detection of antipersonnel (AP) landmines, whose casing is made of plastic, is the principle task of humanitarian demining. Even in a plastic AP-landmine, very small metallic part is included, and it can be detected by a metal detector (MD). Therefore, MD is widely used for Humanitarian Demining. However, the problem of MD is its very high false alarm rate. Ground Penetrating Radar (GPR) is a useful sensor for detection of buried antipersonnel landmines, and we think it can be used for identification of AP-landmines, if it is used together with MD.

A MEXT (the Japanese Ministry of Education, Culture, Sports, Science and Technology) Committee of Experts on Humanitarian Demining Technology presented the report "Promoting Research and Development for Humanitarian Demining" in May 2002. The report showed that research and development based on Japanese advanced science and technology should be carried out for supporting safety and effective activities of Humanitarian Demining in mine affected countries. According to a sector designated to JST (Japan Science and Technology Agency) from the MEXT on ground of this report, JST set a research area, invited research proposals and started the research and development. Under this research project, the research group of Tohoku University has started the development of two mine detection systems, namely ALIS and SAR-GPR in 2002 and completed the prototypes of the systems by 2005.

The combination of GPR and MD has been employed in some landmine detection systems. However, the method of combining two sensors must still be developed. We have introduced a novel technique of tracking the sensor position into a combined MD and GPR sensors, in order to use it as a hand-held system. This is the Advanced Landmine Imaging System (ALIS) sensor system.

SAR-GPR (Synthetic Aperture Radar – Ground Penetrating Radar) is a sensor system developed to be equipped on the Mine Hunter Vehicle (MHV). This system is also composed of a GPR and a metal detector. The GPR employs an array antenna combined with synthetic aperture radar algorithm, and it suppresses clutter and can image buried objects in strongly inhomogeneous material. SAR-GPR is a stepped frequency radar system, whose RF component is a newly developed compact vector network analyzers. In order to achieve a compact and a fast data acquisition system, we developed a new compact network analyzer. The size of the system is 30 cm × 30 cm × 30 cm, composed from six Vivaldi antennas and three vector network analyzers. The weight of the system is 17 kg, and it can be mounted on a robotic arm on a small unmanned vehicle.

For the purpose of contributing to the execution of the Project by the Transitional Administration of Afghanistan, the Government of Japan extended a grant to the Transitional Administration of Afghanistan in accordance with the Exchange of Notes signed in November, 2003. On behalf of the Department of Mine Clearance, Department of Disaster Preparedness of the Transitional Administration of Afghanistan, Japan International Cooperation System (JICS), as an implementing agency selected possible sensors. Under the support of this project, we tested the ALIS in December 2004 in Afghanistan.

GPR for Landmine Detection

GPR is an effective sensor for detection of non-metallic buried objects. However, compared to normal GPR applications, GPR systems for landmine detection is required some special features. Most of the AP-landmines are buried in very shallow subsurface, i.e., less than 5cm. GPR is operated on the ground surface, and the targets are located very close to the antennas for GPR. The strong reflection from the ground surface and the direct coupling between the transmitting and receiving antennas are superimposed on the reflection signal from shallowly buried landmines, and they are normally very difficult to separate. Moreover, the ground surface and shallow soil are strongly inhomogeneous, and they cause very strong clutter.

These factors make the landmine detection by GPR quite difficult. In order to solve these problems, we used the techniques as follows. The frequency bandwidth must be very wide to achieve a high radar range resolution. Our first task was for Afghanistan, therefore, we could assume that the soil is very dry, and the high frequency has not much problem for attenuation. Therefore, we decided to use the frequency range of 1 GHz - 4 GHz.

The clutter caused by the inhomogeneous material masks the refection from the buried landmine. However, if we can use the migration algorithm for reconstruction of the image of the buried objects, we still have a very high possibility for detection of the buried landmines. However, conventional GPR systems for landmine detection did not use the migration algorithm, because the GPR data was acquired without any information about the sensor position. We developed a sensor tracking system for the hand-held landmine detection senor ALIS, to solve this problem.

If we can use a vehicle mounted system, we have much more possibility for signal processing. We designed an array antenna system for SAR-GPR, and used more advanced signal processing algorithm.

ALIS

ALIS configuration and operation

ALIS is a hand-held landmine detection sensor, which is equipped with a metal detector and GPR. In addition, it can track the sensor position while scanning by a deminer in real time. The sensor signals from the metal detector and GPR are stored in a PC together with the sensor position information. All the system is controlled by the PC, which is inside a daypack on the back of a deminer.

Fig. 1 shows the ALIS system under operation. A deminer is scanning the handheld ALIS sensor, and hanging a daypack which contains the operating PC. The deminer is also wearing a head-up display. The same display that the deminer is monitoring is transmitted to a handheld PC display, and several operators can monitor the operation For the usual operation of ALIS, we need one operator who scans the sensor, and another operator who controls and monitors the sensor signal.

The scanning by ALIS follows the exactly same procedure that normal hand-held metal detector is used. A deminer stands in front of the boundary of a safe zone, and scan the area about 1 m by 1 m using the hand-held sensor. We recommend scanning continuously, even when the deminer detects anomalous signal from the metal detector. After scanning the area, we process the acquired data sets using the same PC. Normally, the processing requires one to a few minutes until all the data sets are displayed. Finally ALIS provides a horizontal visualized image of the metal detector signal, and three-dimensional (3-D) GPR information. The information of 3-D GPR is usually too much for interpretation on the site, so ALIS displays horizontal slices (C-scan) of the GPR signal. An operator can move the depth of GPR slice images, and can detect the buried landmine image.

Fig. 1. ALIS system under test at the CDS site in Afghanistan.

Sensor tracking system

A conventional MD sensor outputs audio signal and an operator has to estimate the position of the buried objects only from the sound. If the sensor signal can be visualized, detection of objects can be much easier. Visualization of the sensor is possible, if we can obtain the sensor position together with the sensor signal. However, most of the conventional hand-held sensor could not provide the sensor position. In order to obtain the senor position, we can use a stereo-vision system, which needs at least two camera set around the sensing position. Sensors mounted on a robotic arm can track the sensor position, but the size of the senor becomes larger and is not suitable for a hand-held sensor.

In order to solve these problems, we developed a sensor tracking system by using a CCD camera mounted on the sensor itself and attached it to the MD and GPR sensors. In Fig. 1, two white disks placed near the scanning area are standard positions of the sensor tracking system, and its position is traced in the CCD captured image. Compared to the location of the plastic discs, the sensor position can be tracked in real time. The output signals of MD and GPR are stored in a PC together with the sensor position information. The MD signal is visualized on the CCD captured image and they are projected on a head-mounted PC display of the operator. Three types of information, i.e., CCD image, GPR and metal detector are continuously acquired. However, due to the time required for data acquisition, the sampling data interval is several points per second. Fig. 2 shows an example of the trace of the sensor head scanned manually. Each dot indicates the points where the data was acquired. We can find that the data acquisition points are quite random. Fig. 3 shows the visualized metal detector signal superimposed on the CCD image.

GPR

ALIS uses an impulse GPR system which operates at the frequency range of 1 GHz – 3 GHz. Two orthogonal polarization cavity back spiral antennas are used, and they are mounted in from of the MD coil as shown in Fig. 4(a). This system uses an impulse radar system. We are also developing a stepped frequency GPR system, which uses a Vivaldi-type antenna as shown in Fig. 4(b) (Sato *et al.*, 2004). This type of antenna will be used in combination with a compact vector network analyzer. The system is now under evaluation. Interferences between MD and GPR can be minimized by sensor calibration.

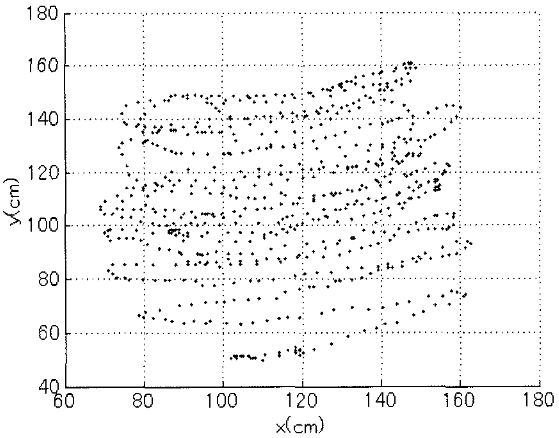


Fig. 2. Data sampling points.

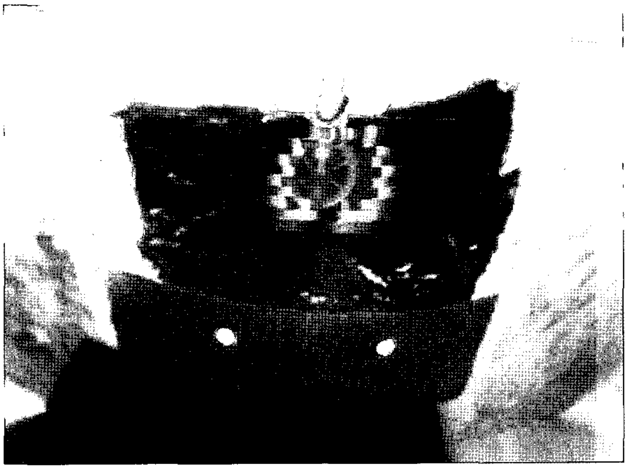


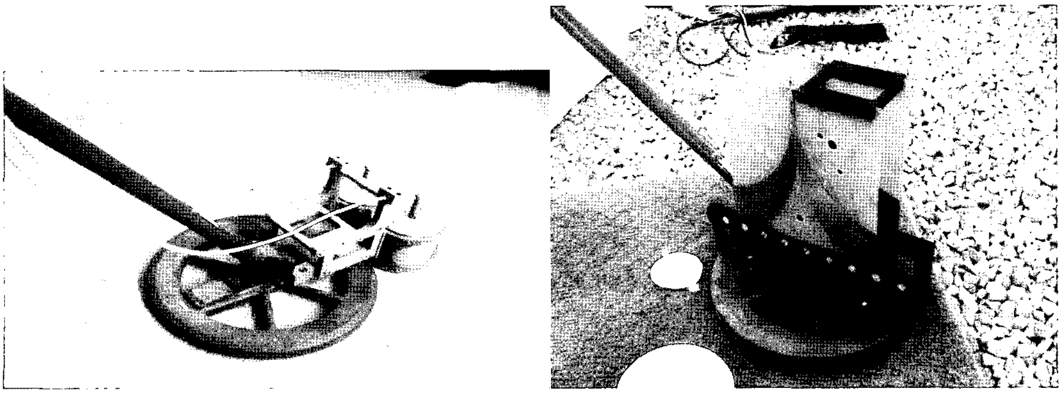
Fig. 3. Visualized metal detector data.

Metal detector

We use a commercial metal detector (CEIA MIL-D1) for ALIS system. More than 2000 sets of this type of metal detector have been operated, and we believe it is one of the most reliable sensors, for landmine detection in Afghan soil condition. The interference of the two sensors, namely GPR and metal detector has been studied. MIL-D1 has a calibration function, and even when metal objects are located near the metal detector sensor, the output signal can be compensated by this calibration procedure. We found that, if the antenna is firmly fixed against the metal detector sensor position, the influence of the existence of GPR antennas can be completely canceled. And the sensitivity of the metal detector to buried objects does not change. However, the influence of the metal detector sensor to the GPR signal is hard to compensate. Therefore, the GPR antennas are mounted in front of the metal detector sensor.

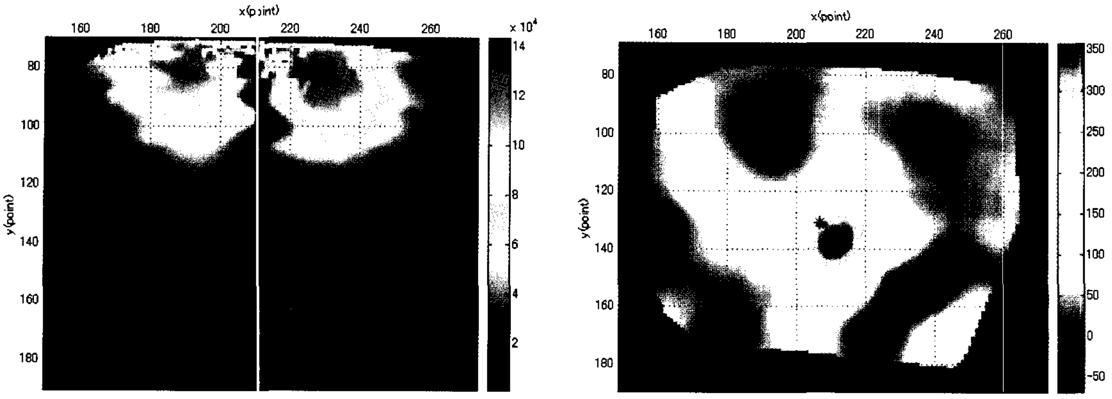
Data processing and display

The GPR data acquired with the sensor position information is processed after the scanning the ALIS sensor over the area of about 1 m by 1 m. At first, all the acquired data set was relocated on a regular grid points. Interpolation algorithm is



(a) Cavity back spiral antenna. (b) Vivaldi antenna.

Fig. 4. GPR antennas and metal detector sensor.



(a) Metal detector image

(b) GPR image

Fig. 5. ALIS output image acquired at CDS test site.

used for this process. After the relocation of the data sets, metal detector signal can directly be displayed in a horizontal image as shown in Fig. 5(a).

3-D GPR image is reconstructed by Kirchhoff migration algorithm. The Kirchhoff migration gives the output wave field $P_{out}(x_{out}, y_{out}, z, t)$ at a subsurface scatter point (x_{out}, y_{out}, z) from the input wave field $\mathrm{Pin}(x_{in}, y_{in}, z = 0, t)$, which is measured on the surface $(z = 0)$. The integral solution used in migration is given by:

$$P_{out}(x_{out}, y_{out}, z, t) = \frac{1}{2\pi}\iint\left[\frac{\cos\theta}{r^2}P_{in}\left(x_{in}, y_{in}, z=0, t+\frac{r}{v}\right) + \frac{\cos\theta}{vr}\frac{\partial}{\partial r}P_{in}\left(x_{in}, y_{in}, z=0, t+\frac{r}{v}\right)\right]dxdy \qquad (1)$$

where v is the RMS velocity at the scatter point (x_{out}, y_{out}, z) and $r = 2\sqrt{(x_{in}-x_{out})^2+(y_{in}-y_{out})^2+z^2}$, which is the distance between the input point $(x_{out}, y_{out}, z = 0)$ and scatter point (x_{out}, y_{out}, z). $\cos\theta$ is obliquity factor or directivity factor, which describes the angle dependence of amplitudes and is given by the cosine of the angle between the direction of propagation and the vertical axis z. $1/vr$ is the spherical spreading factor. The time derivative of the measured wave field yields the 90-degree phase shift and adjustment of the amplitude spectrum. In this signal processing, the vertical inhomogeneity of the soil is considered.

The migrated GPR data gives a 3-D reconstructed subsurface image. However, we normally use only horizontal slice image (C-scan) as shown in Fig. 5(b) for data interpretation. This is due to too much clutter in 3-D image and from many trials, detection of buried landmine image in the horizontal slice is most reliable.

Data acquisition takes a few minutes, which is almost equivalent to the time required for normal scanning operation of a conventional MD, and the signal processing needs about two minutes after the data acquisition. Wireless LAN sends sensor data to a hand-held PC display for judging the image by multiple operators.

SAR-GPR

Concept of Development

We found that the hand-held ALIS works quite well, however, imaging by GPR is very difficult in strongly inhomogeneous material due to strong clutter. We are proposing to use a synthetic aperture radar (SAR) approach to solve this problem, and have developed a SAR-GPR equipment (Sato *et al.*, 2004; Feng and Sato, 2004a). SAR-GPR is a combined sensor tool composed of a metal detector and an array-antenna GPR equipments. When a simple imaging by radar is difficult, we can use a set of scanned radar data for further signal interpretation. This can be achieved by solving inverse scattering problems, but it consumes much time for computation. Another approach is migration signal processing, which are simpler compared to inverse scattering approach, but much simpler and robust. Migration processing, which is often used in geophysical exploration on seismic and GPR, is equivalent to synthetic aperture radar (SAR) processing, widely used in remote sensing.

One of the most important aims of the JST project was the use of unmanned vehicle for landmine detection operation. A few new unmanned vehicles were developed by this project. Mine Hunter Vehicle (MHV) is one of the developed vehicles. This compact vehicle can negotiate tight turns and rough terrain, and safely access to minefields providing fine under-

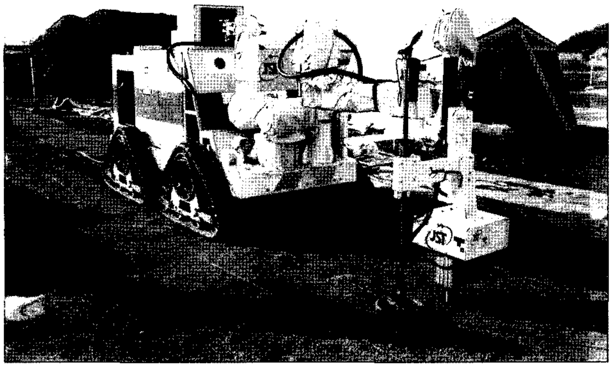


Fig. 6. SAR-GPR mounted on MHV.

ground images. Under the program supported by JST, the SAR-GPR was planned to be used on the MHV. Fig. 6 shows the SAR-GPR which is mounted on the robotic arm of MHV.

Array antenna and data acquisition

Landmines are targets which are buried in shallow subsurface, normally less than 10 cm. A GPR antenna has to have a good electromagnetic coupling to subsurface material, so it has to be set very closely to the ground surface. Hence, the distance to the buried target from the antenna is less than 20 cm. We are designing our GPR for the use in a very dry conditions such as Afghanistan, therefore, we can use relatively high frequency compared to conventional GPR applications, which normally use a frequency up to 1 GHz. We adopted an antipodal Vivaldi antenna for our GPR, because it has relatively sharp radiation pattern in very broad frequency range, and it requires no balance-unbalance transformation (Feng *et al.*, 2005a; 2005b; http://www.jst.go.jp/kisoken/jirai/EN/index-e.html). At the same time, this type of antenna can be fabricated easily, and suitable for an array antenna. We used FDTD for designing the antenna, and the prototype antenna showed a good operation in the frequency range of 1 GHz and 4 GHz.

The antennas will be scanned mechanically near the ground surface and acquire the radar data. The data will be processed afterwards for subsurface imaging. At the same time, we use an array antenna having six elements for data acquisition, in order to suppress the ground clutter. We adopt a Common Midpoint (CMP) technique for gathering a data sets acquired at one position by the array antennas (Feng and Sato, 2004b). The same antennas shown in Fig. 4(b) are used for SAR-GPR array antenna.

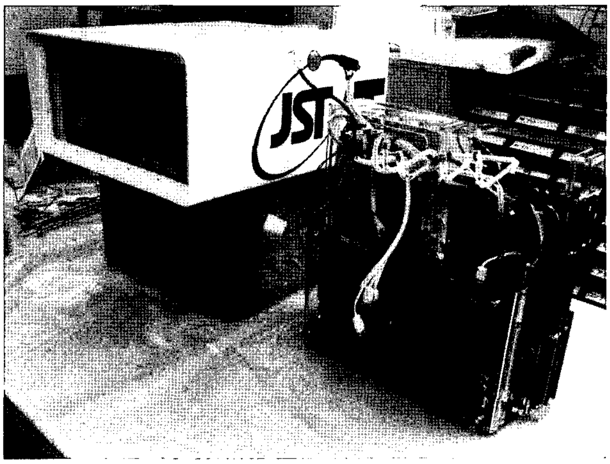


Fig. 7. Vector network analyzer for SAR-GPR.

Compact vector network analyzer

In order to achieve the optimum SAR-GPR performance, selection of adaptive operational frequency is quite important. Also, antenna mismatching causes serious problems in GPR. Most of the conventional GPR systems employ impulse radar, because it is compact and data acquisition is fast. However, most of the impulse radar system had disadvantages such as instability in signal, especially time drift and jitter, strong impedance mismatching to a coaxial cable, which causes serious ringing, and fixed frequency range. Vector network analyzer is synchronized transmitter- receiver measurement equipment. It is composed of a synthesizer and coherent receiver. It enables quite flexible selection of operation frequencies, and stable data acquisition. In addition, commercial vector network analyzers are equipped with a calibration function, which masks impedance mismatching caused by RF hardware. Impedance matching of antennas to coaxial cables in GPR is quite difficult in all the frequency range of operation. Therefore reflection caused by impedance mismatching returns to a generator, and signal wave deforms. In order to avoid these effects, many GPR antennas adopt strong damping by impedance loading, which decreases antenna efficiency. If we use a vector network analyzer, reflection from antennas can be perfectly absorbed by the vector network analyzer, therefore, we can operate antennas without heavy impedance loading.

However, due to the large size and weight, conventional network analyzer cannot be mounted in SAR-GPR. Compact vector network analyzer has been available, which can be used field measurement. However, this existing compact vector network analyzer had limited frequency range, which cannot be adopted in GPR for landmine detection, and data acquisition speed was too slow for practical use. Therefore, we decided

Table 1. Comparison of commercial and developed vector network analyzers (VNA)

	Developed VNA	MS4624	E5071B
Measurement	S21	S21, S11, S22	S21, S11, S22
Operation condition	–20 - +50°C		
Frequency	100 MHz - 4 GHz	10 MHz - 9 GHz	300 kHz - 8.5 GHz
Dynamic range	70 B	125 dB	122 dB
Acquisition rate	646 pt/sec	6,500 pts/s	1,000,000 pts/s
Accuracy	± 1 dB	± 1.5 dB	± 1 dB
Power supply	DC12-15V10W	100-200V, 540W	100-200V
Size	250X170X60	352X222X457	
Weight	3 kg	25 kg	17.5 kg

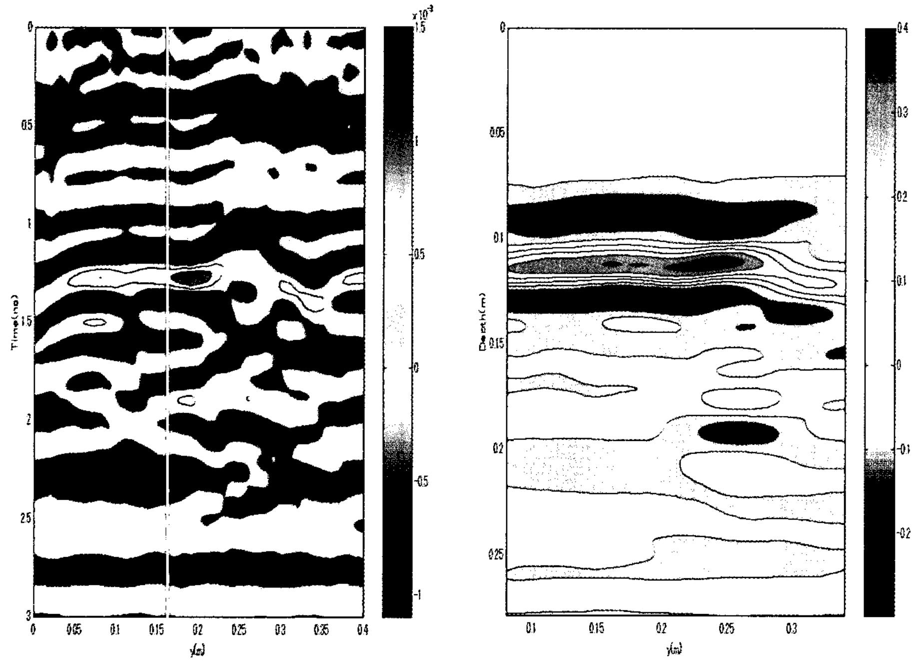


Fig. 8. Vertical section of SAR-GPR image.

to develop a new compact vector network analyzer shown in Fig. 7 which fits to our requirements. Table 1 shows the comparison of the specifications of commercial and new vector network analyzers.

Image reconstruction algorithm

The signal processing used for SAR-GPR is similar to that used for ALIS, however, the data acquisition accuracy and density is much higher in SAR-GPR, and we can use more advanced concepts of signal processing in SAR-GPR. Two stage signal processing was carried out after the acquired data had been transformed into time-domain data by inverse Fourier transformation. At first, the CMP stacking was carried out for suppression of ground clutter. In this processing, 5 data sets acquired at one position are stacked by calculating the time delay differences due to different propagation length between antenna sets. Clutter from the ground surface and homogeneous gravel can be suppressed by this CMP processing. The stacked signal is then processed by the diffraction stacking algorithm and a 3-D image is reconstructed.

Laboratory evaluation test

Test measurement was carried out using a sandbox in laboratory condition, which simulates very rough ground conditions. A sand box was filled with gravels having a diameter of about 50 mm and crashed rocks having a diameter of about 5 mm. The averaged dielectric constant of the mixed material is about 3.8, which was determined from the radar measure-

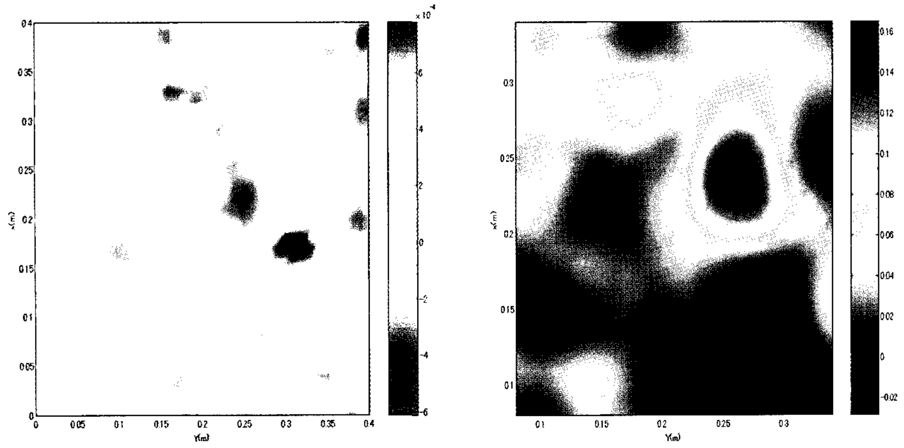


Fig. 9. Horizontal section of SAR-GPR image.

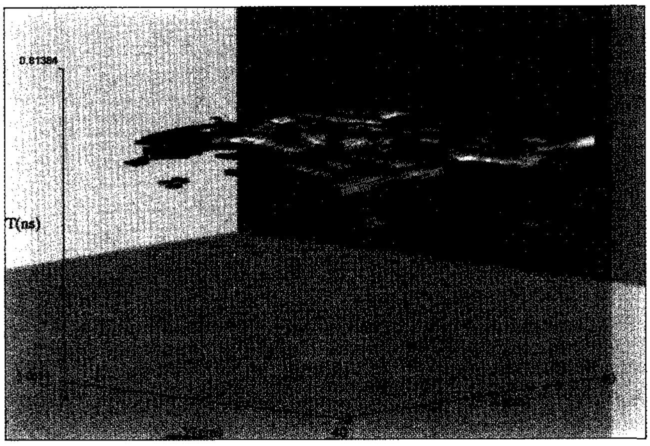


Fig. 10. Common offset Raw GPR profile.

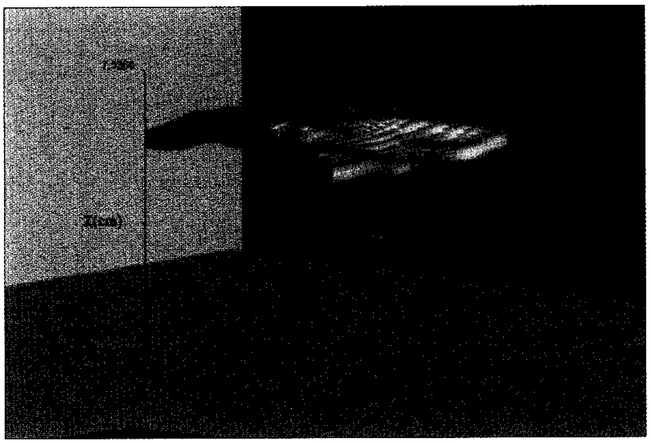


Fig. 11. Processed GPR profile after CMP stacking and migration.

ment. The correlation length of the ground surface is 20 mm and the RMS height is 15 mm. The radar target is a model of a plastic landmine Type-72. It contains very small amount of metal part, and it is mostly filled with dielectric material. This model has a cylindrical structure having a diameter of 78 mm and the thickness is 40 mm. The antenna array was moved by a horizontal X-Y stage and acquired the radar data at 1cm interval. The antenna height from the mean ground surface was about 50 mm. Fig. 8 and Fig. 9 show the GPR images of CMP stacked data, before and after SAR processing. Fig. 10 and Fig. 11 show the 3-D GPR reconstructed images. The effect of SAR processing is very clear and only after SAR processing, buried landmine image can be clearly found in soil. Now we can distinguish the reflections from the buried landmine model and the ground surface separately.

Metal detector

We believe that detection of buried landmine from GPR image is too difficult in practical situation, because the GPR mages always suffer from artifacts caused by strong clutter, even when in SAR-GPR signal processing was adopted. Therefore, all the judgment of data is carried out by combination of metal detector information. CEIA MIL-D1 sensor was equipped on the SAR-GPR system, and the metal detector signal is visualized at the same time.

Evaluation test in Afghanistan

After laboratory tests, we have conducted field evaluation test of ALIS in Kabul city, Afghanistan in December 2004. Field test was conducted at two locations. The first site (CDS site) was a controlled flat test site, prepared for the evaluation of landmine sensors. The second site (Bibi Mahro Hill) is a small hill inside Kabul city, which is a real landmine field, where demining operation was being carried out.

At the CDS site, we could validate the operation of the

ALIS for known targets in various conditions. The climate when we conducted the field tests was partly rainy, and water content of the soil at CDS site was about 10%, corresponding to the dielectric constant of 5.3. Real PMN-2 and Type 72 landmines without booster were buried at the CDS site at different depths between 0 and 20 cm, and we could find that the metal detector can detect landmines buried shallower than 15 cm, and GPR can show clear images of landmines, which are buried up to 20 cm in depth. We also found that the metal fragments, which were included in the soil, did not showed clear GPR images, therefore we could discriminate metal fragments from landmines by ALIS.

Fig. 12. Bibi Mahro Hill in Kabul, Afghanistan.

Bibi Mahro Hill shown in Fig. 12 is a real landmine field, and we buried a PMN-2 plastic shell model filled with TNT

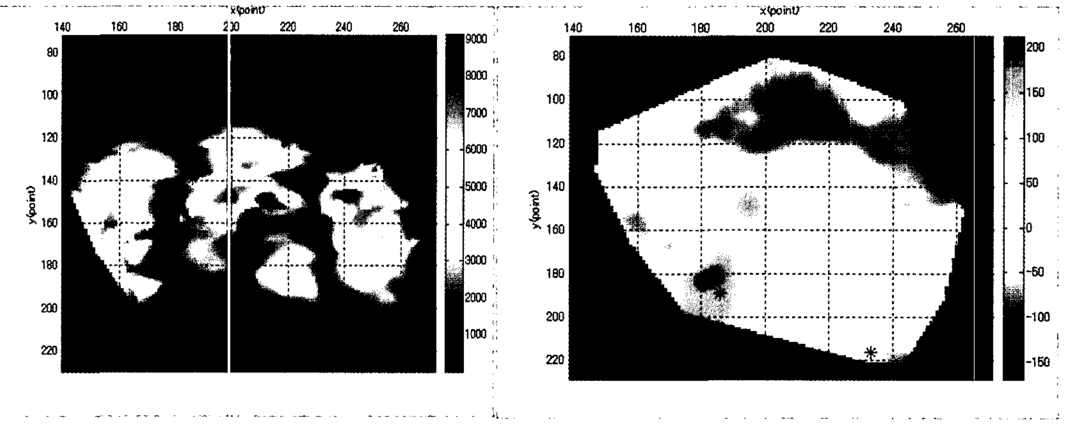
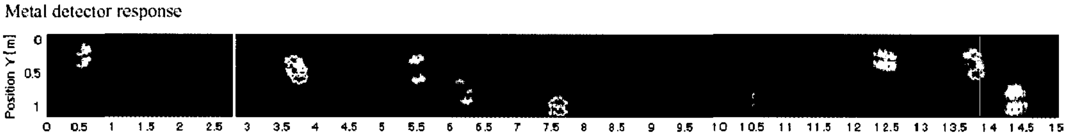
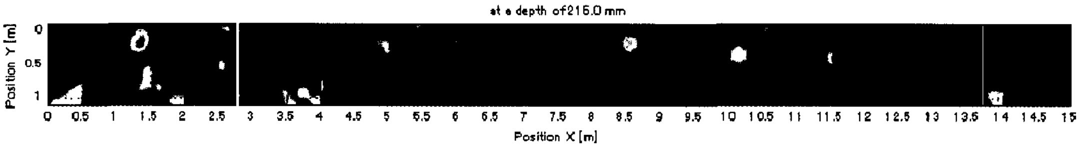


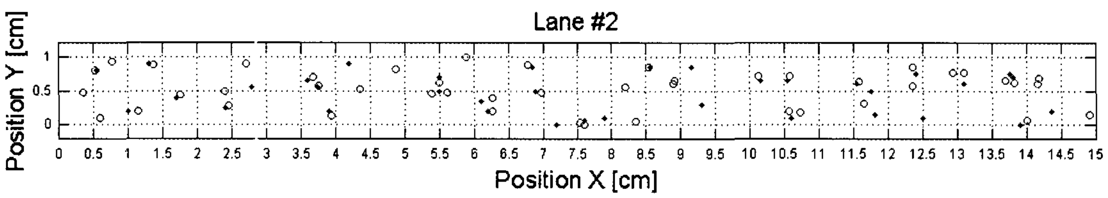
Fig. 13. ALIS visualization output at Bibi Mahro Hill, Kabul city, Afghanistan.



(a) Metal detector image



(b) GPR image



(c) Interpreted locations of the buried landmines

Fig. 14. SAR-GPR output in test in Japan

explosive and put a small metal pin in it imitating the metallic part of a booster of the real landmine. In addition, we buried a small metal fragment about 15 cm apart from the landmine model. Fig. 13 shows the ALIS visualization output at Bibi Mahro Hill. Fig. 13(a) is the MD image, and we can find two separated metal objects in the figure. CEIA MIL-D1 has a differential signal output, and a single metal object shows symmetric response, having a null point at the center. Fig. 13(b) shows the GPR image, and we can find only one clear image, which correspond to the landmine model. Note that the center of the two sensors differs by 20 cm, and then the images in Fig. 13 have 20 cm offset.

Evaluation Test in Japan

An evaluation test was carried out in Kagawa, Japan in March 2005. This is the final domestic evaluation test for all the developed sensors in the JST project. 6 test lanes, each is 2 m by 15 m lane, filled with different kind of soil were prepared. A part of the lane was used for sensor calibration, and the other part was used for blind test. Fig. 14(a) and (b) show the metal detector and GPR image obtained by the SAR-GPR. Using the two images, we estimated the location of the buried landmines as shown in Fig. 14(c). We could detect almost all the buried landmines, when the ground surface is relatively flat.

Currently, we are planning to evaluate SAR-GPR mounted MHV in Croatia in spring 2006.

Conclusion

We developed ALIS, which has high efficiency with better reliability for landmine detection by MD-GPR sensor fusion. The developed ALIS can visualize the signal, although it is a hand-held sensor. ALIS was evaluated in real mine field in Afghanistan and we could demonstrate its high ability. We are planning to replace the GPR by stepped frequency system, and it will increase the flexibility of the system, because we can select operation frequency range on site.

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