An Impulse Radar Array for Detecting Land Mines

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An Impulse Radar Array for Detecting Land Mines

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Abstract – The Lawrence Livermore National Laboratory has developed radar and imaging technologies with potential application in demining efforts. A patented wideband (impulse) radar that is very compact, very low cost, and very low power, has been demonstrated in test fields to be able to detect and image non-metallic land mines buried in 2-10 cm of soil. The scheme takes advantage of the very short radar impulses and the ability to form a large synthetic aperture with many small individual units, to generate high resolution 2-D or 3-D tomographic images of the mine and surrounding ground. Radar range calculations predict that a vehicle-mounted or man-carried system is quite feasible using this technology. This paper presents the results of field tests using a prototype unit and describes practical mine detection system concepts. Predicted capabilities in terms of stand-off range and radiated power requirements are discussed.

1. Introduction

A new radar technology, Micropower Impulse Radar (MIR), has been tested to evaluate its viability as a mine detection sensor. The tests have shown that MIR reliably detects both plastic and metallic landmines buried in moist soil. The MIR sensor technology provides several advantages over existing ground-penetrating radar (GPR) systems including: low cost, low power RF output, light weight and compact size, and the ability to assemble into compact arrays. Coupled with 2-D and 3-D imaging algorithms, the MIR offers a potential for a low cost, high performance mine detector that will enhance the reliability and performance of multisensor mine detection systems. This paper describes the new sensor technology and presents examples of its capabilities. In addition, it discusses results from the recent field tests and describes system concepts for vehicle-mounted and hand-held mine detectors.

Prior to the MIR development, LLNL has investigated and developed GPR technology for land mine and unexploded ordnance detection. A system that was assembled and field tested could be mounted on an airborne platform[1]. That system successfully detected metallic land mines and land mine surrogates buried in a minefield located at the Nevada Test Site. The system also detected plastic mines, but with significantly lower detection reliability. The system used a 3 kV pulse transmitter at a stand-off distance of 9 meters.

2. MIR Technology

The Micropower Impulse Radar was developed at LLNL in 1993 as an outgrowth of the development of the R&D 100 Award Winning Single-shot Transient Digitizer (SSTD). The SSTD records very high speed transient events in the Laboratory's high power pulsed Nova laser. The compact MIR circuit module shown in the photograph in Figure 1 is a complete impulse radar transceiver which is constructed using low cost, off-the-shelf components.
A variety of antennas have been designed to attach to this unit. The transmit and receive antennas used for mine detection are resistively loaded cavity backed dipoles measuring about 4 cm on a side. With the antennas connected to the radar, the entire radar element fits in a 4 x 6 x 10 cm volume. The technical specifications of the single radar element are summarized in Table 1. It should be noted that these units emit very low RF power in a broad RF band, and so are virtually undetectable. This is particularly important as a safety issue when searching for the types of mines that may detonate when irradiated by microwaves.

3. MIR Imaging with Arrays

For mine detection and imaging, high resolution in both range and cross-range is desired. High range resolution is achieved using the ultra-wide-bandwidth of the MIR transmitter. The 100 ps rise time pulse yields range resolution of about 2 cm in typical soils. Although the higher frequency components of the RF pulse do not penetrate well in soil (typically 45 dB/meter loss at 3 GHz), the mines are typically not buried very deep (usually no more than 10 cm since they must remain sensitive to ground contact) so the loss factor is not a significant source of image degradation.

Cross-range resolution is achieved by forming a synthetic aperture array of MIR elements. Since the elements are fairly low in cost (about $10 parts count) it is feasible to connect several elements in a linear array to span the desired aperture. Alternatively, a single radar element can be scanned along a line while collecting samples at regular interval spacing, thus forming a 1-D array. The resolution achieved depends on the wavelength, range, the single element beam pattern, the element spacing, and the overall dimension of the aperture.

The aperture size for a linear array is typically chosen to be the field-of-view (beam width) of a single element times the range to the target. This gives the widest possible span of look angles from the radar to the target, and also provides the maximum sensitivity to cross range position of the target. Element spacing is typically chosen no larger than the single-element antenna size. This will prevent any imaging artifacts due to aliasing.

Although the object is typically in the near field of the antenna array and the image formation algorithm is based on near field diffraction theory (diffraction tomography), the rules for array design appear to be basically the same as those generally used for far-field imaging.

In our field tests, we used a 1 meter aperture with 1 cm element spacing (100 synthetic array elements) and achieved cross range resolution of a few cm at 10 cm depth in soil.

To achieve high resolution in both cross-range directions, it is necessary to form a 2-D synthetic array. In the field experiments, we did this synthetically by scanning a single MIR element in a raster scan pattern. In a demining operation it is more practical to use a 1-D array and scan once in the orthogonal dimension to form the synthetic 2-D aperture.

LLNL has developed the diffraction-tomography based imaging software necessary to reconstruct the 2-D and 3-D images[2]. This software had previously been developed as a tool for GPR inspection of steel-reinforced concrete bridge decks. The software is written in portable C code, and can run on a workstation or laptop portable computer. 2-D images of a single cross-sectional slice in the ground can be reconstructed from raw data on a 486 laptop in about 1 minute. Since the tomography code can be parallelized, it is not inconceivable that a dedicated multiprocessor based on (say) power PC chips can produce 3-D images from raw data at a similar rate.
4. Field Tests

To evaluate the feasibility of using MIR as a mine detection sensor, a prototype MIR module was incorporated in a test system that could be used to make measurements in the field. A single MIR module was used for collecting radar data, synthesizing 1-D and 2-D arrays in "look-down" mode. The system consisted of a prototype MIR unit (with characteristics described in Table 1), a lap-top computer for gathering the data, and a fixture used to support and move the mine sensor over target areas. Figure 2 is a photograph of the system collecting field data.

The field tests were conducted at the Buried Object and Mine Detection Facility at the Nevada Test Site (NTS). Real antitank and anti-vehicular mines (with high explosives but without detonators) and mine surrogates, both plastic and metallic, have been buried at this facility. Figure 3 shows typical placements of M-15 and VS-2.2 mines before being covered with soil. Natural vegetation, rocks and rubble, and animal burrows were left intact when the mines were buried to maintain realistic conditions. The soil in the test area is made up of alluvium, consisting of Paleozoic fragments and tuff. Soil conductivity is in the range of 5 to 8 millisiemen. The soil during these radar tests was slightly moist, due to rain the day before, with the topmost few millimeters being dry.

The NTS field tests showed conclusively that real plastic mines buried roughly 5 cm beneath the surface can be readily detected and imaged by the MIR system. Metal mines (such as the M-15) showed a strong reflection from the top of the mine. Plastic M-19 and VS-2.2 mines showed reflections from both top and bottom mine surface and a characteristic resonance behavior. Figure 4 shows a sequence of 2-D constant depth slices from the 3-D reconstructed image of an M-19 plastic antitank mine. Note that the square shape of the mine, its depth in the soil, and its vertical extent, are all clearly evident in the image sequence. Figure 5 shows a similarly reconstructed image of a VS-2.2 plastic antitank mine. Its circular cross-section shape is evident in this sequence. The reconstruction of particular details of these mines shows that they have unique MIR signatures which could be used to differentiate them from natural objects like rocks or roots. Buried rocks of roughly the same size as these mines were also imaged by the MIR system at the NTS site.

A similar test field at LLNL contains surrogate (empty of high explosives) antipersonnel and antitank mines with both plastic and metal casings. Many of these mine surrogates are smaller than those at NTS, and the soil is quite different, mostly wet clay. Radar imaging tests have shown that these surrogates are also visible to the MIR system.

5. Mine Detection System Concepts

Vehicle-mounted and man-portable mine detection systems are needed for demining operations in both low and high clutter environments. MIR arrays and image reconstruction software can be readily integrated into viable multisensor systems that address both needs.

For low clutter environments, like roadways, a linear array of MIR modules configured in a "look-ahead" operating mode and mounted on the front of a remote-controlled ground platform can be used to detect anti-tank and anti-vehicular mines. In this configuration, MIR modules are assembled into an array positioned so that its field-of-view covers an area of 2 to 4 square meters, a few meters in front of the ground platform. Radar data is telemetered via wireless, fiber optic, or hard-wired connection to the remote control point, where image processing and display hardware are located. Data acquired from the array is used to make 2-D images of the area in front of the vehicle.

In higher clutter environments, like off-road areas, a linear array of MIR modules
can be configured for "look-down" operation to detect anti-tank and anti-personnel mines. The array is mounted on a boom extending in front of the remote-controlled vehicle to provide an appropriate standoff distance between the vehicle and the area being surveyed. In this case, the MIR array is mounted so that its field-of-view covers an area of 2 to 4 square meters below the array. The array is scanned so that a 2-D aperture is synthesized. Again, radar data is telemetered to the remote control point. Data acquired from the synthetic array is used to reconstruct 3-D images of the scanned area. This approach is useful in areas where vegetation and other surface obstacles are present, since target position and burial depth, with respect to soil surface, can be determined from the reconstructed image. Surface clutter sources can be identified and removed from the image, if they are determined by other vehicle-mounted sensors not to be mines, so that the buried objects can be detected, classified, and marked.

Man-portable mine detection systems may also be required in demining operations. In areas where terrain, foliage, and other obstacles preclude the use of remote-controlled detection systems, man-portable detection techniques may be the only methods available. Compact size, lightweight, and low cost make MIR technology an excellent candidate for these systems. Imaging arrays can conceivably be developed that operate in the "look-ahead" mode and quickly produce 2-D maps of areas searched by human operators.

6. MIR in Mine Detection Applications: Technical Requirements

Some modifications are required to adapt current MIR module technology for the system concepts described in the previous section. Several development activities already underway address these needs. For example, ongoing design improvements in the MIR receiver will integrate a low noise, wideband amplifier into the front-end, reducing the noise figure to 4 to 5 dB and extending the dynamic range to 98 dB. Impulse generator development work is also underway to integrate step recovery diodes into the transmitter output stage to increase bandwidth and peak power. These changes will permit MIR modules and arrays to operate at stand-off ranges required for vehicular and man-portable mine detection systems used in demining operations. Finally, work is progressing on antenna and antenna lens design to tailor antenna gain and radiation patterns for the needs of a variety of applications.

A preliminary analysis of requirements for the MIR modules used for mine detection is given below, and summarized in Table 2. The required peak radiated power is calculated assuming that a single pulse return signal of 10 dB above the background noise is necessary for detection. The background noise is given by

$$\text{noise} = kT\text{BW}\text{nf}$$

where $k$ is Boltzman's constant, $T$ is temperature in degrees Kelvin, BW is receiver bandwidth, and nf is receiver noise figure. For $k = 1.4 \times 10^{23}$, $T = 290 ^\circ K$, $\text{BW}=10$ GHz, $\text{nf} = 6$ dB, noise is $8 \times 10^{-10}$ watts (-63 dBm). The received signal power is

$$P_r = P_t A G_d \sigma \xi_a^2 \xi_r^2 / (4 \pi R^2)^2$$

where $P_t$ is the peak transmitter power, $A$ is the receiver antenna area, $G_d$ is the antenna directive gain, $\sigma$ is the target cross-section, $\xi_a$ is the attenuation loss from propagation in soil, $\xi_r$ is the reflection loss at the soil-air interface, and $R$ is the target range.

The reflection loss at the soil surface is

$$\xi_r = 1 - \rho^2$$

$$= 1 - [(\nu e_s - \nu e_a) / (\nu e_s + \nu e_a)]^2$$
where $e_s$ and $e_a$ are the relative dielectric constants of soil and air, respectively. The attenuation loss is 30 dB/meter in soil at 1.5 GHz and 45 dB/meter at 3 GHz.

The target cross-section depends on the target reflection coefficient according to:

$$\sigma = \pi a^2 \left( \sqrt{e_s} - \sqrt{e_m} \right) / \left( \sqrt{e_s} + \sqrt{e_m} \right)$$

where $e_m$ is the relative dielectric constant of the mine, and $a$ is the mine radius. To calculate values in the table, we assume $e_a = 1$, $e_s = 8$, $e_m = 3.5$, $a = 10$ cm, $G_d = 1$, and $A = 10$ cm$^2$. The mine is assumed buried at a depth of 5 cm.

In all of the cases shown in Table 2, the MIR modules each transmit 10 microwatts of average power. We use this power level as a design example to show that a practical mine detection radar can be kept in the micropower range. An array of 100 units will transmit a total average RF power of only one milliwatt. The pulse repetition frequency (PRF) is then adjusted to keep the average power at 10 microwatts according to

$$\text{PRF} = \frac{P_{\text{ave}}}{(P_t \, \tau_t)}$$

where $P_{\text{ave}}$ is the average power, $P_t$ is the peak power, and $\tau_t = 100$ ps is the pulse width.

7. Summary

Micropower Impulse Radar and imaging technology developed at LLNL have direct applicability to the demining problem. Feasibility tests at buried object test sites have demonstrated the reliable detection of both metallic and plastic cased mines. Such a sensor could be used to improve detection and decrease the false alarm rates in multisensor mine detection systems. Ongoing development activities at LLNL, including the constriction of a linear array and improvements to the receiver sensitivity and antenna design, will adapt the current MIR technology to practical mine detection system requirements.

Acknowledgment

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References


### Table 1. Micropower Impulse Radar imaging module characteristics.

<table>
<thead>
<tr>
<th>General</th>
<th>Monostatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Configuration</td>
<td>Monostatic</td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>5 cm (height), 10 cm (width), 10 cm (depth)</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 0.23 kg</td>
</tr>
<tr>
<td>Input Power</td>
<td>6 to 12 volts, 8 mA</td>
</tr>
<tr>
<td>Range (Maximum)</td>
<td>Up to 10 m in air; 0.2 to 0.5 m in soils (depends on soil conductivity and standoff range)</td>
</tr>
</tbody>
</table>

### Transmitter

| Type | Ultra-wide-bandwidth, impulse waveform |
| Pulse Repetition Frequency | 2 MHz |
| Pulse Rise-time (Radiated) | ~100 psec |
| Bandwidth | 3.2 GHz (from ~0.8 to 4.0 GHz) |
| Radiated Power (ERP) | < 100 mW, peak; < 10 µW, average |
| Antenna: Cavity-backed, resistively-loaded monopole |
| Beamwidth (-3 dB) | 120° |

### Receiver

| Front End: Equivalent-time sampler with sensitivity-time control |
| Bandwidth | < 4.0 GHz |
| Noise Figure | 25 dB |
| Antenna: Cavity-backed, resistively-loaded monopole |
| Beamwidth (-3 dB) | 120° |

### Table 2. MIR module requirements for mine detection applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Stand-off range (m)</th>
<th>Radiated peak power (W)</th>
<th>Radiated average power (µW)</th>
<th>Maximum PRF (Kpps)</th>
<th>Receiver dynamic (dB)</th>
<th>Antenna beamwidth (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Look-ahead&quot; vehicle-mounted</td>
<td>2 to 3</td>
<td>52.7</td>
<td>10</td>
<td>1.9</td>
<td>90</td>
<td>60 to 75</td>
</tr>
<tr>
<td>&quot;Look-down&quot; vehicle-mounted</td>
<td>0.5 to 1</td>
<td>0.75</td>
<td>10</td>
<td>133</td>
<td>90</td>
<td>75 to 90</td>
</tr>
<tr>
<td>&quot;Look-ahead&quot; man-portable</td>
<td>1 to 1.5</td>
<td>3.5</td>
<td>10</td>
<td>28</td>
<td>90</td>
<td>60 to 75</td>
</tr>
</tbody>
</table>
Figure 1. Printed circuit board for a Micropower Impulse Radar module.

Figure 2. Test system collecting data from a minefield at the Nevada Test Site.
Figure 3: Typical plastic mine placement before burial.
Figure 4. Reconstructed image sequence for an M-19 plastic mine.

Figure 5. Reconstructed image sequence for a VS-2.2 plastic mine.