A new densely-sampled Ground Penetrating Radar array for landmine detection

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***Abstract*— Clearing large civilian areas from anti-personnel landmines and cluster munitions is a difficult problem. The FP7-funded research project 'TIRAMISU: Toolbox Implementation for Removal of Anti-personnel Mines Sub-munitions and UXO' aims to develop a global toolbox that will cover the main mine action activities, from the survey of large areas to the actual disposal of explosive hazards to mine risk education. For close-in detection a number of tools are being developed, including a new densely-sampled down-looking Ground Penetrating Radar array. It is a vehicle-based imaging array of air-launched antennas, endowed with real-time signal processing for the close-in detection (~0.4 m stand-off) of landmines and UXOs buried within ~0.5 m deep soil layer. Automatic target detection capabilities and integration with a partner's metal detector array onto a suitable autonomous vehicle will increase field data productivity and human safety. In particular, a novel antenna design has been studied to allow dense packing and stand-off operation while providing adequate penetration and resolution in almost all kind of terrains. Great effort is also being devoted to the development of effective signal processing algorithms suited for real-time implementation. This paper presents the general system architecture and the first experimental results from laboratory and in-house tests.**

***Index Terms*—Air-launched antenna, densely-sampled GPR array, Humanitarian Demining, TIRAMISU project.**

I. INTRODUCTION

Clearing large civilian areas from anti-personnel landmines and other explosive hazards, such as Unexploded Ordnances (UXO), is a very difficult problem. Rather than a single solution a comprehensive toolbox is required from which mine action operators can choose the tools best fit to a given situation. In humanitarian demining the FP7-funded research project 'TIRAMISU: Toolbox Implementation for Removal of Anti-personnel Mines Sub-munitions and UXO' aims to provide mine action operators with a modular integrated solution covering all the main mine action activities, from the identification of hazardous areas, to the survey of large areas, to the actual disposal of explosive hazards, to mine risk education [1].

In mine action after the identification of hazardous areas by means of non-technical survey, a major role is played by close-in detection, i.e. the use of suitable (combination of) hand-held or vehicle-based sensors deployed close to the ground surface for the detection of shallow underground landmine/UXOs. Although metal detector (MD) is the most widely used sensor, Ground Penetrating Radar (GPR) is increasingly employed as a complementary tool for reducing the false alarm rate of MD caused by metal clutter and to improve the detection of low-metal (plastic) mines. Therefore, for landmine detection MD and GPR are often combined into dual sensors. Although there are standard procedures for test and evaluation of metal detectors [2], there are only guidelines for testing GPR or dual-sensor since soil properties affect GPR in a more complex way [3]. Mainly within research projects MD and GPR are integrated with other sensors, e.g. chemical, biosensors, etc. [1], [4], [5].

Successful research has been conducted for the development of hand-held combined MD+GPR sensors (and the relevant signal processing), such as the ALIS prototype [6], [7] in order to improve the detection of shallow landmines by trained operators even in difficult terrains. However, hand-held systems suffer from low productivity and high risk for the deminer safety. Although less mature than hand-held detectors, vehicle-based, remotely-controlled (either stand-alone or combined) detection systems are able to provide wider coverage and reduce risks for human safety [5], [8].

Within the TIRAMISU project a number of tools are being developed for close-in detection, including a new densely-sampled, down-looking GPR array [9]. Past experience in utility mapping and archeology has demonstrated that the use of ground-coupled, densely-sampled GPR arrays [10] yields dramatic improvements over single-channel systems for imaging underground objects and identifying subtle features which otherwise would be undetected, while increasing field productivity.

Two major challenges in landmine detection are the need of:

- using air-launched, rather than ground-coupled, antennas in order to prevent activation of the mines and facilitate surveying on rough terrains;

- keeping the spatial sampling along the array axis as small as possible for detecting/resolving decimeter-size objects.

In order to fulfill the above requirements, within the TIRAMISU project, intensive research has been devoted to the study and laboratory testing of a novel antenna design suitable for air-launched deployment in a densely-packed GPR array for close-in detection of landmines and UXOs buried within ~0.5 m deep soil layer.

An ongoing activity is the development of signal processing algorithms, including automatic target detection (ATD) capabilities, suitable for real-time implementation.

In 2014 the GPR prototype will be integrated onto a remotely-controlled vehicle and tested in the field. Finally, the tool will be demonstrated in an operational environment (Croatia field trials) by the end of the project (2015).

This paper presents the general system architecture and the first experimental results from laboratory and in-house tests.

II. SYSTEM ARCHITECTURE

A. Overview and schematic description of the GPR system

An overview of the architecture of the GPR system, including interfaces with the carrying platform and other sensors of the close-in mine detection system, is given in Fig. 1 and Fig. 2. The field deployment is similar to commercial ground-coupled massive GPR arrays used in utility mapping [10], except for the mechanical integration with the vehicle that is modified in order to keep the array suspended in air at a suitable distance (up to ~0.4 m) from the ground. The system is endowed with distance measuring instrument (DMI) providing local positioning reference and absolute coordinate measuring device (ACMD), consisting of (differential) global positioning system (GPS) or inertial measuring unit (IMU), providing absolute positioning reference for geo-referencing the GPR data for data fusion with data from a partner's MD array.

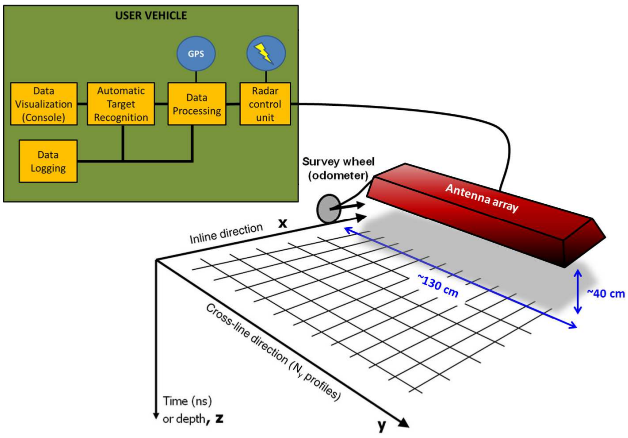

Fig. 1. Schematic drawing of the GPR system for mine detection

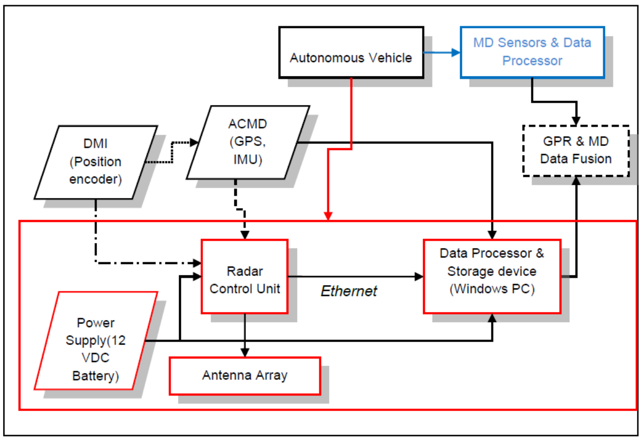

Fig. 2. GPR system architecture and main interfaces with the other blocks of the close-in mine detection system.

This impulse GPR system has been developed with the goal of increasing the productivity with respect to hand-held sensors while maintaining the performance and the reliability of the results. To this aim data collection has to respect the constraints on spatial sampling along both the inline and cross-line direction (Nyquist criterion), which is fundamental to allow a correct 3D reconstruction of the volume inspected.

Previous tests using a ground-coupled 600 MHz dense array have successfully detected metallic and plastic anti-personnel (AP) mines and other ordnances buried up to 0.8 m in a moderately conductive soil. Due to the lower penetration depth usually required in humanitarian demining, higher frequency (~1 GHz) has been chosen for the new array as a trade-off between improving the resolution (useful for detecting small AP mines) and preserving adequate depth penetration (~0.5 m) in unfavorably conductive soils (essential for deeper UXOs).

B. The antenna subsystem

The GPR array is a multichannel antenna array allowing the survey of a ~1.3 m wide swath in a single pass. Data acquisition is driven by an ultra-fast radar control unit that guarantees high acquisition speed (up to 1400 scans/s @ 512 samples/trace). Therefore, collecting data on a square grid of 4 cm by 4 cm (adequate to fulfill the Nyquist criterion in both directions) the system can be towed up to 6.5 km/h (1.8 m/s), which is comparable or higher than typical speeds of robotic or other remotely controlled platforms used as sensor carriers in humanitarian demining.

The dense cross-line spacing has been made possible by the use of a novel antenna, suitably slim for dense packing and purposely designed for deployment in air-launched arrays. It is known that the radiation pattern of ground-coupled dipoles (such as classical bow-ties) depends, among other parameters, on the antenna height above ground and severely degrades as the antennas are raised above the ground surface, due both to impedance mismatch and the insurgence/increase of reflections from above-surface objects. Therefore strong efforts have been devoted to investigating whether different antenna types, such as resistively-loaded Vee-dipoles (RVD) [11], could be better suited for application as air-launched antennas in terms of radiation characteristics (in addition to other requirements like bandwidth, size, weight, technological complexity, etc.).

An antenna simulation tool has been developed and an intensive parametric analysis has been performed to assist the antenna design for optimizing its performances in the chosen frequency range. For instance, the simulations with an RVD in air (similar to Fig. 3) show that, even at short range (near-field zone), appropriate resistivity loading is beneficial for reducing side-lobe radiation and preserving good directivity properties at all interesting frequencies (Fig. 4).

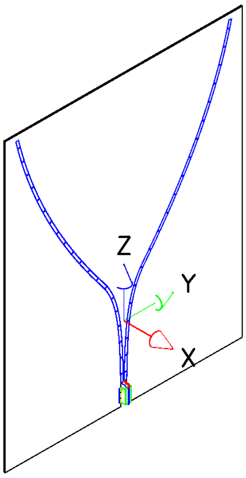

Fig. 3. Isometric view of an RVD antenna

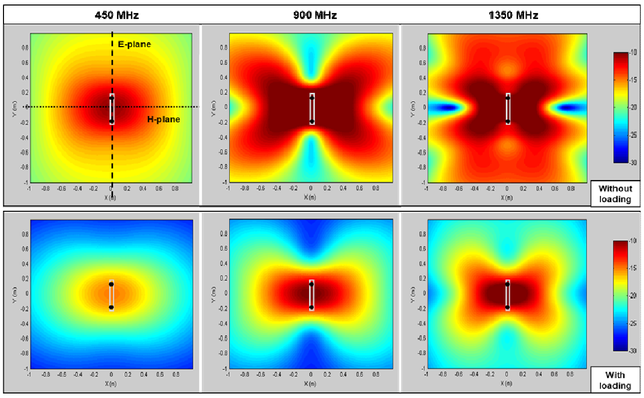

Fig. 4. Simulated near field (dBV/m) of Vee dipole without (top) and with resistive loading (bottom)

C. Signal processing

Common practice in humanitarian demining involving GPR or dual-sensors usually relies on operator experience in interpreting radar data and discriminating actual targets from false alarms. Addressing a frequent user requirement for some automatic way to help reducing the influence of the "human factor" over the reliability of results, an expected major progress within this project is the improvement of automatic detection capabilities so that the operator does not need to have GPR interpretation skills. The goal will be achieved by upgrading the most successful signal processing strategies developed in the course of past demining projects and including new signal and image processing tools, such as time-frequency analysis, for detection and classification of targets. An ongoing activity is the development of real-time processing able to handle the relatively large data rate and give detection results within a definite and suitable time lag. This involves the selection of appropriate (fast) algorithms for clutter reduction and automatic target detection procedures, as well as the adoption of cutting-edge visualization tools to facilitate human-machine interaction. Since even for vehicle-mounted GPR arrays assisted detection by a suitably trained operator could be superior to fully automatic detection algorithms, this feature is useful for post-mission assessment of the automatic results and for validation purposes.

III. EXPERIMENTAL RESULTS

A. Laboratory tests (antenna characterization)

Prototypes of RVD antenna printed on a sheet of dielectric substrate have been realized and several laboratory tests have been performed to verify the real antenna performances by measuring the following parameters trough a vector network analyzer (VNA):

- the antenna impedance and Voltage Standing Wave Ratio (VSWR);
- the antenna radiation pattern on the two main planes (E-plane and H-plane);
- the antenna boresight gain versus frequency.

These measurements show that the antenna has nearly flat, real impedance in the 0.5 ÷ 3 GHz frequency band (Fig. 5). According to the boresight gain (Fig. 6) the antenna has a ~1.4 GHz wide band (at -3 dB) from 0.8 GHz to ~2.2 GHz centered at 1.5 GHz. In addition, the measurements of the radiation pattern on the two main planes show that the antenna beamwidth (at -10 dB) is ~60 degrees in the E-plane and ~100 degrees in the H-plane.

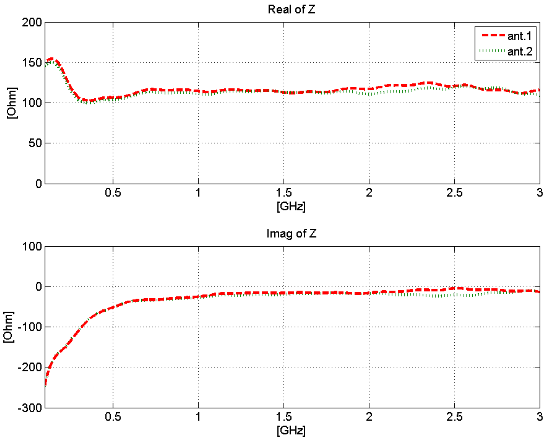

Fig. 5. Impedance of two RVD prototypes

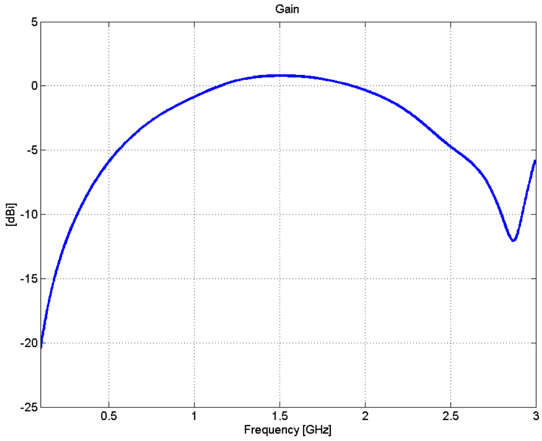

Fig. 6. Gain vs Frequency of the RVD prototype

B. In-house tests of the GPR array

In-house tests have been devoted to verify the overall antenna performance once the radiating elements have been connected through standard transmitters and receivers to the radar control unit. The tests over a perfect electric conductor (PEC) placed 40 cm from the antenna aperture (Fig. 7) show that the effective bandwidth at -3 dB is ~850 MHz (from 550 to 1400 MHz) and the central frequency is 975 MHz, both lower than the corresponding intrinsic antenna parameters. This is caused by the actual transmitter that boosts the low frequencies at the expenses of the high-frequency part of the spectrum. Despite this, the bandwidth seems adequate for the purpose of the project. In particular, low frequencies are less prone to being attenuated from underground conduction losses and hence low-frequency content is essential for preserving adequate depth penetration (~0.5 m) in unfavourably conductive soils.

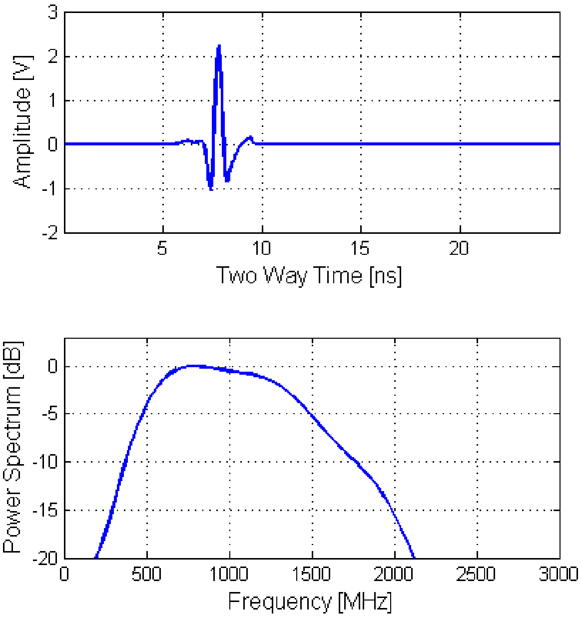

Fig. 7. Measured reflection from a metal plate at 40 cm from the RVD antenna aperture in the time and frequency domain

The first prototype of new densely-sampled array of air-launched antennas for landmine detection, named LUCIFER, is shown in Fig. 8. Preliminary tests, conducted in April 2013 over a controlled test site with buried pipes (Fig. 9), have shown the possibility of imaging targets more than 1 m deep in favourable soils.

Fig. 8. The new densely-sampled array of air-launched antennas

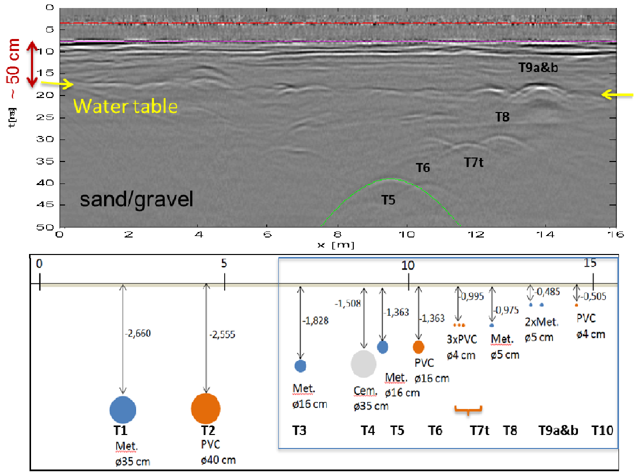

Fig. 9. Tests of the array over a controlled test-site with pipes (top: B-scan after cross-coupling removal; bottom: cross-section of the buried pipes)

Other tests are being conducted over test sites with various soil types in order to understand the effective performances of the GPR system in relatively controlled situations and the influence of moisture conditions, stand-off of the array, presence of nearby sources of above-ground interference. In particular, the last point is relevant to assessing possible interference from (metallic) structures of the carrying vehicle and to identify mitigation measures.

Moreover, these tests aim to assist the development of the real-time processing software and validate its results. For instance Fig. 11 shows the results of the processing chain at various stages on the data collected above the targets shown in Fig. 10. It is clear that the applied processing is effective in detecting the true targets and discriminating them from clutter or soil inhomogeneity. Processing algorithms are being continuously improved to yield similar results also in less favourable soil conditions.

Fig. 10. Example of canonical targets (½” metal pipe and Ø 5cm metal sphere) in homogeneous sandy soil

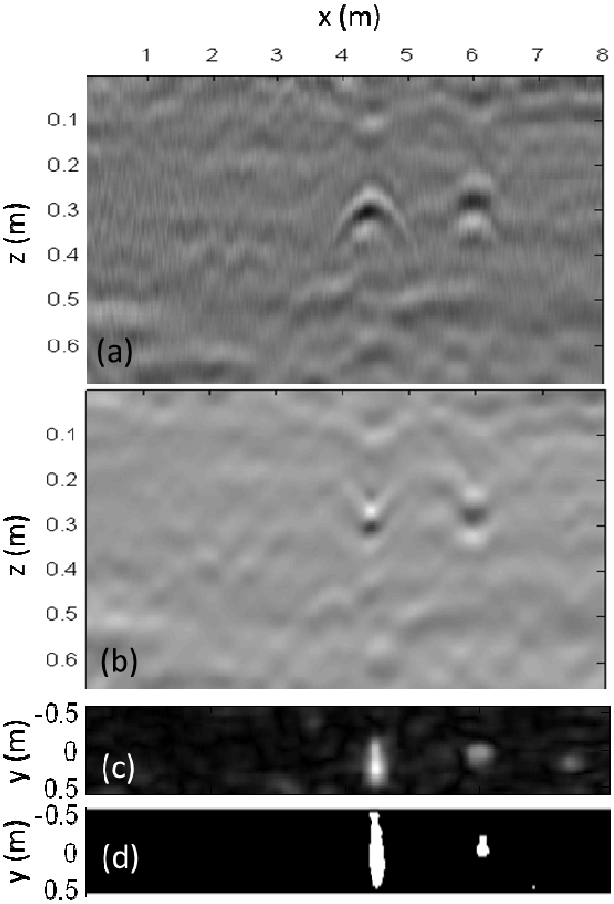

Fig. 11. Experimental results above the canonical targets of Fig. 10. (a) B-scan after pre-processing. (b) Migrated B-scan. (c) Migrated C-scan at 0.3 m depth. (d) 2D plan view of ATD at raster stage.

IV. CONCLUSION

A new densely-sampled GPR array for landmine detection based on novel air-launched antenna design has been realized within the FP7-funded research project TIRAMISU. The preliminary results obtained so far with the first prototype are quite encouraging. Further tests (in controlled environment as well as in operational scenarios) will give valuable clues for improvements and refinements of the array. They will also give insights for fine tuning the processing software which is currently being developed.

Major challenges to be addressed in the near future are vehicle integration as well as data fusion of information coming from GPR and from the metal detector array developed by a partner of the TIRAMISU consortium.

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