Modern Trends in Development and Application of the UWB Radar Systems

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***Abstract*—This paper discusses modern requirements for, and approaches to, design of a multi-sensor robotic radar system for humanitarian demining, and a through-wall imaging radar. In addition, we review progress in use of UWB radar systems for investigation of objects and structures representing important historical and cultural heritage. A review of the special European action intended for progress in civil application of UWB radar is also presented.**

***Keywords*— UWB; radar, probing, imaging, GPR, holographic radar**

I. Introduction

UWB electromagnetic waves of a few GHz frequency range are able to penetrate through many types of materials. These form the basis for ground penetrating radar (GPR), and they allow us to investigate what is in the ground, behind opaque walls, under rubble, and other surfaces. Accordingly, rescue and human security are some of the most promising fields for applications of UWB radars. In addition, recent developments of femtosecond lasers for terahertz imagine and corresponding receiving equipment have made it possible to investigate the internal structure of paintings, mosaics, and so on.

In spite of the relatively young age of UWB systems, they have managed to enhance many practical and useful tasks. Several actual problems, which are currently under investigation, are described in this paper. Section II describes current approaches to humanitarian detection of landmines, UXO, and IED. Modern requirements for UWB through-wall imaging radar and their design is the topic of Section III. Some achievements and results from internal sounding of cultural resources are discussed in Section IV. Section V is devoted to information on the European organization "European Cooperation in Science and Technology" (COST) which unites the top experts working in the area of civilian application of UWB GPRs.

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II. Humanitarian Demining

As reported by the United Nations Office for Disarmament Affairs (UNODA) [1] every day, people are killed or maimed by stepping on landmines, even in peaceful (but post-conflict) countries. The majorities (79%) of the victims are civilians and almost half of them (46%) are children.

A. On explosive objects, which were disarmed by pyrotechnic sub-units of State Emergency Service of Ukraine (SESU) during humanitarian demining in Donetsk and Luhansk regions

Since July 6, 2014, just after the liberation of the first Ukrainian city (Slavyansk) from separatist groups, the pyrotechnics sub-unit of the SESU has continuously engaged in humanitarian demining of the Donetsk and Luhansk regions. These efforts have cleared a land area of more than 11300 hectares (113 km2) and water totaling 38 hectares. About 1000 critical facilities of social infrastructure and life support have been demined, with more than 51300 explosive devices destroyed.

During humanitarian demining, pyrotechnic personnel of SESU detected, removed, and destroyed the following types of ammunition: artillery shells, mortar shells, ammunition for multiple rocket launchers, cluster munitions, various grenades, and engineering (demolition) ammunition, and anti-tank and anti-personnel mines.

B. Holographic and Impulse Subsurface Radar for Landmine and IED Detection

To assist Ukraine, the NATO Science for Peace and Security (SPS) Program funded the international project G5014-“Holographic and Impulse Subsurface Radar for Landmine and IED Detection” [2]. The team consists of scientists from Dipartimento Ingegneria dell'Informazione Università di Firenze (Italy), Usikov Institute for Radiophysics and Electronics of the NAS of Ukraine (Ukraine) and the Department of Earth & Environment at Franklin and Marshall College (USA).

Project tasks include:

- to compare the GPR detection performance for landmines, UXO and IEDs under different soil conditions using existing holographic and impulse radars, electromagnetic induction, and infrared imaging;
- to construct a high spatial resolution scanner for subsurface object detection and classification using new holographic and impulse radars, combined with technologies described above, and possibly including acoustics;
- to develop target classification algorithms for the scanner (based on shape, dimensions, and casing/component material characteristics) to make substantial progress in both the detection rate and minimization of the rate of false alarm, and increase scanning speed.

In order to solve these tasks it is necessary to quantify the effects of soil texture, mineralogy, surface roughness, and moisture content and moisture chemistry on the probability of detection and probability of false alarm for existing holographic and impulse radar, electromagnetic induction, acoustic, and thermal methods; and then to combine the best-performing methods in a single, multi-channel, high-resolution automated scanner.

As a result, the project will identify existing highly portable, low-cost detection technologies, quantify their performance under realistic and variable field conditions, combined the best-performing technologies into a still-portable, and still-low-cost combined-sensor system, and develop target recognition methods that are effective, and operable by relatively untrained personnel.

Fig. 1 shows the main components (blocks) of the system. The robotic system (labeled as 1 in the Figure) moves the high resolution scanner with sensors (labeled as 2 in the Figure) through the minefield. It is equipped with, for example, a Wi-Fi communication system (labeled as 3 in the Figure) allowing the operator (labeled as 4 in Figure 4) to remotely control movement of the sensors and data (from a safe location), and provides transfer of the collected data to the powerful field computer (labeled as 5 in the Figure). Processed data goes to the operator in real time in order to make a fast decision about the nature of the object (mine labeled as 6 in the Figure) before the vehicle passes over it. An advanced approach consists of using artificial intelligence in the field computer which, after sufficient training, can make autonomous decisions about object identities.

Among the other sensors it is intended to use a positioning system [3] which georeferences the data, or associates the collected data to the real position on the ground.

It should be noted that multi sensor approach does not limit the number and kind of sensors to be used for scanning. Owing to this, it can elevate the efficiency and reliability of mine detection in may environmental conditions, making it globally adaptable.

Most importantly, quantifying the critical parameters of probability of detection and probability of false alarm for the integrated system obtained by data processing in the remote computer allows confident prediction of the outcome and safety of humanitarian demining efforts with the system in the hands of minimally-trained operators. This makes the system usable by locals rather than requiring experts from half a world away. The remote operation will diminish casualties among demining personnel and civilians. The entire system could be highly transportable and easily deployed to remote locations.

This project includes development of a classification algorithm based primarily on multiple frequencies with holographic radar, but supplemented by additional sensors. This is an important task of the project because it will simplify the use of the equipment in the field by end users who have no specific training in image processing and analysis. In other words, the aim is to make target recognition as "idiot proof" as possible. The classification methods could be based on a neural - network approach or (and) pattern recognition.

Such technology makes it possible to reduce the cost of

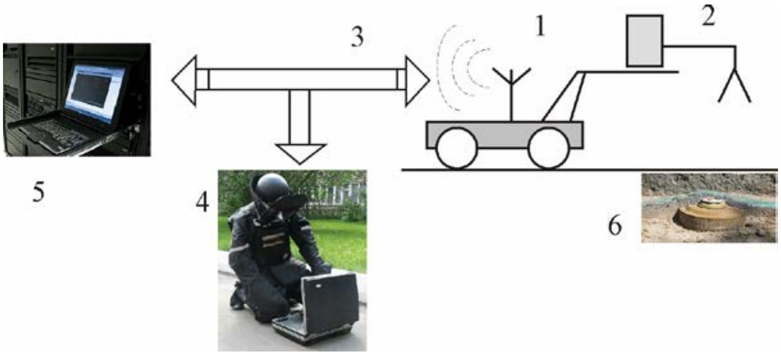

Fig. 1. Common approach to system configuration. 1 is the robotic platform, 2 is sensor (holographic radar or impulse radar or metal detector or others), 3 is a wireless communication system, 4 is a sapper, 5 is a supercomputer, 6 is a target to be detected (mine).

demining, creating the opportunity for broader-scale clearance with the same amount of funding. The ultimate goal of the Project G5014-“Holographic and Impulse Subsurface Radar for Landmine and IED Detection”, and following projects, is a fully autonomous robotic sapper combining multiple sensors (GPR, EM, infrared, acoustic, etc.).

III. Through the Wall Imagine

The possibility to detect, locate, and track moving targets behind a solid wall is important in combating crime and terrorism in the urban conditions. A recent book [4] contains a comprehensive discussion on inverse scattering approaches along with theoretical and experimental research in all problems arising in development of through-wall imaging systems. These systems use different methods such as 3D tomography based on microwave remote sensing, various synthetic aperture radar (SAR) techniques, impulse radars, and others.

The ability to construct radars that simply detect movement is now widespread. However, the current requirement is to provide real time imaging with frame-rates comparable to video. In this case, intuitive interpretation of radar imagery by untrained personnel becomes easier, and any operator can monitor persons or objects moving beyond an opaque wall.

In order to achieve this, the radar must be of high resolution. This means a large and fast data stream. So, it is necessary to provide very rapid radar data acquisition and real-time processing. A possible solution to this problem is given in [5]. While the time-division multiplexed MIMO array architecture is sufficient to provide higher imaging rates, the high-speed SAR imaging architecture originally developed for real-time interferometric synthetic aperture microscopy [6] can be used to increase the frame rate to over 10 Hz. High performance microwave components support this. In addition, an analog-to-digital converter with main characteristics of 1.25 MSPS at 16 bits, and a standard PC can be used in the radar. A so called "pipelined data throughput" and streamlined processing algorithm to interface to the radar system must be used to achieve frame-rate imaging comparable to video.

In the paper [6]

- the time-division multiplexed MIMO radar design is discussed;
- the data acquisition pipeline is described;
- the real-time imaging algorithm is presented;
- initial results of experiments that were conducted in free-space and through a 10 cm concrete wall are shown.

The most important block of this system is a FMCW radar (Fig.2) that transmits linear, frequency modulated, chirps from 2-4 GHz with a cycle time of 1 ms. Peak transmitter power is 2 W. A range gate is implemented by the use of high-Q intermediate frequency filter. This filter rejects returns from the air-wall boundary. In this way, the design provides maximum dynamic range and sensitivity to targets behind a wall, as well as range resolution.

The antenna system consists of 13 transmitting elements and 8 receiving elements (each of them a Vivaldi antenna). This allows for 44 bi-static antenna element combinations acquiring one range profile per pairing. Effective phase centers of antennas approximate a linear array spaced at $\lambda/2$. Such an array makes it possible to get high resolution in the direction along the array axis.

All antennas are connected to a corresponding generator and low noise amplifiers by means of solid state switches that are digitally controlled by the computer. The computer controls the switches, synchronizes the transmitter, and digitizes the video. The data acquisition system consists of multithreaded software executing on a PC and DAQ card (PCI-Express M-Series PCIe-6251).

This radar provides range resolution using the migration algorithm, which is a near-field SAR imaging algorithm. Because processing a single image with this algorithm takes large computer resources, some possible values are pre-computed and stored in the memory whenever possible. A real-time beamforming algorithm was designed to execute a high-speed hardware optimized range migration algorithm.

The radar subtracts the previous raw data set from the current one then displays the difference image in order to provide frame-to-frame change detection. This makes possible a real-time display of the moving target. It shows changes between frames and removes static radar clutter. The SAR (video) image is displayed at a rate of 10.8 Hz. Each image is computed during the time when the data acquisition pipeline is controlling the radar and acquiring new data.

In summary, experiments show that this through-wall radar is capable of locating a human behind a 10 cm concrete wall providing video frame-rate imaging at 10.8 Hz. Furthermore, a human target swinging a large metal pole was imaged even in a high clutter environment. It is expected that this system will locate moving humans at distance up to 20 m and through a 20 cm-thick concrete wall.

IV. Preservation of Historical and Cultural Heritage

Development of technology allowing generation, transmission, reception, and processing of electromagnetic

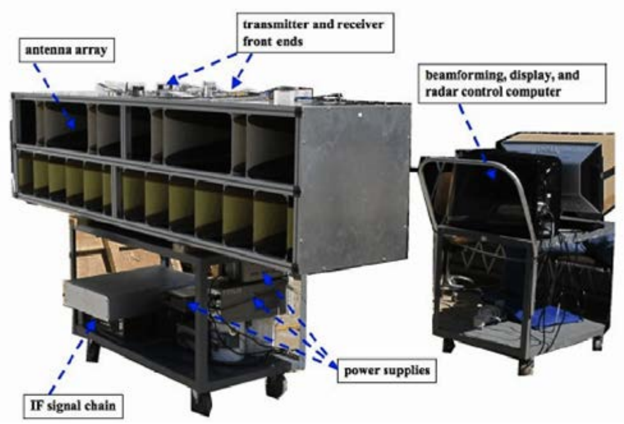

Fig. 2. Radar system (cited from [5])

signals with femtosecond duration has opened new possibilities for new applications of GPR for targets such as the internal structure of paintings, mosaics, etc. that may have historical and cultural significance. Recently, a number of papers have been published on this topic. This section will present some examples of sounding results and the equipment employed.

Paper [7] presents nonlinear imaging as well as terahertz time-domain spectroscopy and imaging as tools for investigations and diagnostics of different artworks. It was shown that nonlinear imaging provides precise and in-depth information. Terahertz imaging detects hidden objects and reveals highly absorptive organic compounds whose visualization is difficult in other parts of the electromagnetic spectrum. Thus, terahertz time-domain systems show features that cannot be seen in optical or X-ray images.

Another paper [8] recounts investigation of the painting “Sacrifice to Vesta” by Spanish artist Goya. The layout of the terahertz time-domain imaging system is shown in Fig. 3. Using this technique it becomes possible to detect details of the artwork (e.g. the signature of author) that are hidden to visible, infrared, or X-ray inspection methods, and that could prove invaluable for tasks such as authentication of artworks.

Terahertz time-domain imaging has also been used for imaging a hidden portrait and other subsurface composition layers of an 18th century easel painting by N. Abildgaard [9]. Interfaces between layers of the paint have been successfully imaged.

Fig. 4 demonstrates results of investigation of the painting "The Dying Messalina and Her Mother" from paper [10] where we can see visible image of the investigated area, its X-ray radiograph, peak-to-peak time parametric THz image, and others. Notice that a hidden portrait in the painting has been imaged by terahertz time-domain imaging. Terahertz time-domain imaging and x-ray radiography are particularly complementary tools for the investigation of art objects.

The VIth Conference on “Diagnosis, Conservation and Valorization of Cultural Heritage” was held on December 10-11, 2015 in Naples (Italy). About 13 papers presented at this conference are devoted to problems of nondestructive diagnostics of historical and cultural objects. Among of them such papers as "On the use of THz waves to characterize bacteria attacks on marble samples" [10], and "THz surveys of mortar samples: advantages and limits" [11]. There was also

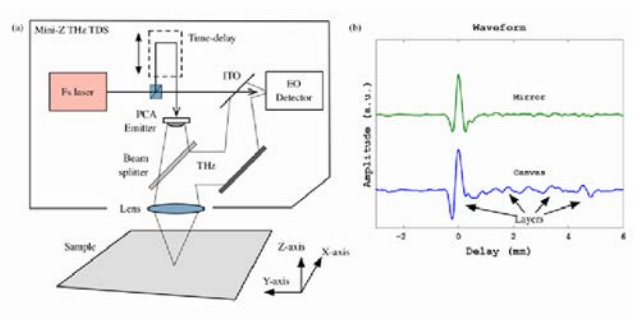

Fig. 3. Experimental layout of the terahertz time-domain imaging system (cited from [8])

the IWAGPR2015 conference where the invited talk by K. Fukunaga is titled “THz pulse-echo imaging applied to cultural heritage” [12]. These titles highlight the range of tasks where UWB radars are now useful.

V. COST Action TU1208

European Cooperation in Science and Technology (COST) was founded in 1971 for the transnational coordination of nationally-funded research activities [13]. This European framework is based on agreement between the governments of 36 European countries and cooperating States. COST is intended for conversion of the newest scientific achievements into technologies that provide future progress.

For European researchers, COST became a means for communication, collaboration, and development of their ideas by means of trans-European networking of research activities.

Within the framework of COST, there is an Action TU1208 [14] the aim of which is to share new knowledge in the area of GPR obtained by scientists from national research institutes, with the goal of advancing safe and non-destructive testing techniques into the field of civil engineering. In general, scientists from 40 countries are cooperating in the framework of the Action TU1208 (Fig. 5).

Now the term of activity (term of grant) of the COST Action TU1208 is defined from 4 April 2013 to 3 April 2017.

The Action is divided on four working groups (WG) according to the nature of researches.

WG1: Novel GPR instrumentation*;*

WG2: GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing;

WG3: Electromagnetic methods for near-field scattering problems by buried structures; data processing techniques;

WG4: Different applications of GPR and other NDT technologies in civil engineering.

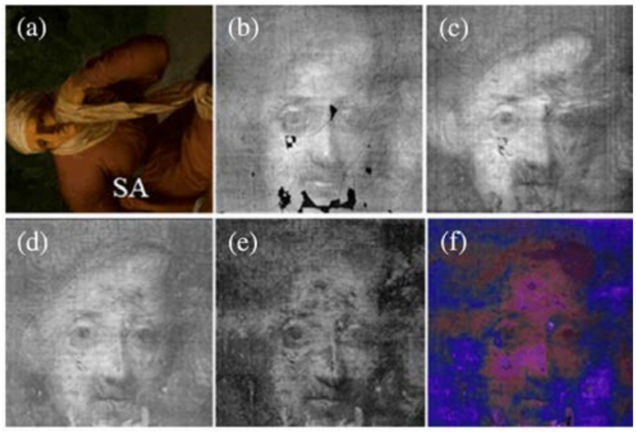

Fig. 4. (a) Visible image of the scanned area. (b) X radiograph of the scanned areas. (c) Peak-to-peak time parametric THz image. (d) THz frequency integrated image of interface layers included among I2 and I3. (e) THz image in the 0.55–0.62 THz range. (f) THz false color image.(cited from [9])

Fig. 5. Countries which participate in the Action (cited from [13])

Networking Tools for COST Action TU1208 are:

- Meetings, workshops, conferences;
- Training schools;
- Short-term scientific missions;
- Dissemination activities.

CONCLUSIONS

As a conclusion we can state that UWB radiolocation is actively developing technologies providing new and sometimes unexpected possibilities for practical applications in a wide range of fields of interest. This paper has shown only a few directions where UWB radar systems are yielding new, unique, and important results. The cooperation of researchers from a number of different countries contributes greatly to the progress.

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