SAFEDRONE project: development of a UAV-based high-resolution GPR system for IED detection

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***Abstract*—This contribution presents the main objectives and achievements of the SAFEDRONE project, devoted to the development of airborne-based high-resolution Ground Penetrating Radar (GPR) systems for the detection of buried landmines and Improvised Explosive Devices (IEDs). The overall goal of the project is to take advantage of the ability of Unmanned Aerial Vehicles (UAVs) to enable a contactless, safe, and fast scanning of the area of interest, together with the capability of Synthetic Aperture Radar (SAR) systems to provide high-resolution radar images. Down-Looking and hybrid Forward-Looking/Down-Looking architectures have been tested throughout the project in order to determine which of them provides the best detection results (depending on the scenario, and geometry, composition, and depth of the buried targets). To achieve the required accuracy to enable GPR-SAR processing, precise positioning and geo-referring subsystems have been integrated within the UAV. Results of the validation tests conducted in realistic scenarios are presented.**

***Index Terms*—Ground Penetrating Radar (GPR), Synthetic Aperture Radar (SAR), Improvised Explosive Devices (IEDs), non-destructive inspection, Unmanned Aerial Vehicle (UAV).**

I. INTRODUCTION

Safe and accurate detection of buried threats such as Improvised Explosive Devices (IEDs) and landmines is of vital importance for humanitarian and military demining campaigns. Different technologies have been introduced to address this major challenge, ranging from metal detectors, magnetometers, thermal cameras, and Ground Penetrating Radar (GPR), among others.

GPR is a versatile and efficient technology for landmine and IED detection as it allows detecting both metallic and non-metallic targets, provided there is enough contrast between the constitutive parameters of the target and the soil. GPR capability to detect buried targets depends on the working frequency band. In this regard, lower frequency bands provide greater penetration depth, but at the expense of usually poorer resolution (as at lower frequencies most systems are narrow band) [1],[2].

Improvements in Unmanned Aerial Vehicle (UAV) technology together with advances in radar and telecommunications, have facilitated the development of advanced airborne-based landmine and IED detection systems. For example, [3] makes use of an airborne radar at X band and Synthetic Aperture Radar (SAR) processing to detect IED command wires. GPR radars have been successfully integrated within UAVs in [4]-[9] for landmine and IED detection. These systems operate in frequency bands ranging from 400-600 MHz up to 4-5 GHz, as they provide a good trade-off between penetration depth and resolution.

This contribution presents some of the UAV-based GPR prototypes and architectures conceived and experimentally validated within the framework of the SAFEDRONE project, one of the first research and development projects fully devoted to the improvement and demonstration of this kind of technology. In particular, two of the implemented architectures will be described, together with a summary of the results of the first validation and testing campaign.

II. DESCRIPTION OF THE PROJECT

The main goals of the SAFEDRONE project are:

1. Improvement of the detection capabilities of existing airborne-based GPR systems. This encompasses the integration of enhanced radiofrequency and positioning hardware, and the design and implementation of several pre and postprocessing techniques. These techniques, which include clutter reduction strategies, aim to maximize the detection probability of buried threats.
2. Design and implementation of several GPR architectures, assessing their advantages and limitations. In particular, i) a Down-Looking GPR (DL-GPR) system, ii) a hybrid Forward-Looking-Down-Looking architecture (FL-DL-GPR), and iii) a DL-GPR system with an array of transmitting and receiving antennas (to increase the survey speed) were developed.
3. Validation on-ground of the payload and the processing techniques and validation of the manufactured prototypes in realistic scenarios, as similar as possible to operational conditions. On-ground validation is significantly important as in-flight validation introduces additional uncertainties and operational complexity, so a proper on-ground validation of the payload is conducted before integrating it within the UAV.

The project also comprises the implementation and integration of a long-range communication subsystem to enable beyond-line-of-sight data transmission between the UAV and the ground station that receives and processes the measurements. Results of the mid-project validation campaign are shown in this contribution and further results corresponding to the final validation campaign (performed in October 2021) will be presented at the conference.

III. DOWN-LOOKING GPR ARCHITECTURE

The background of the SAFEDRONE project is the UAV-based GPR prototype operating in the 3-5 GHz frequency band presented in [9]. The architecture of this prototype was a DL-GPR configuration, as this GPR architecture provides better dynamic range than FL-GPR, but at the expense of more clutter coming from the air-ground interface.

A. *Overview of the system*

The DL-GPR prototype has been improved throughout the SAFEDRONE project in terms of both hardware and software. A picture of the prototype highlighting its main components and subsystems is shown in Fig. 1. Concerning the GPR subsystem, it comprises an Ultra-Wideband (UWB) radar and three Vivaldi antennas covering the 600 MHz to 6 GHz frequency band.

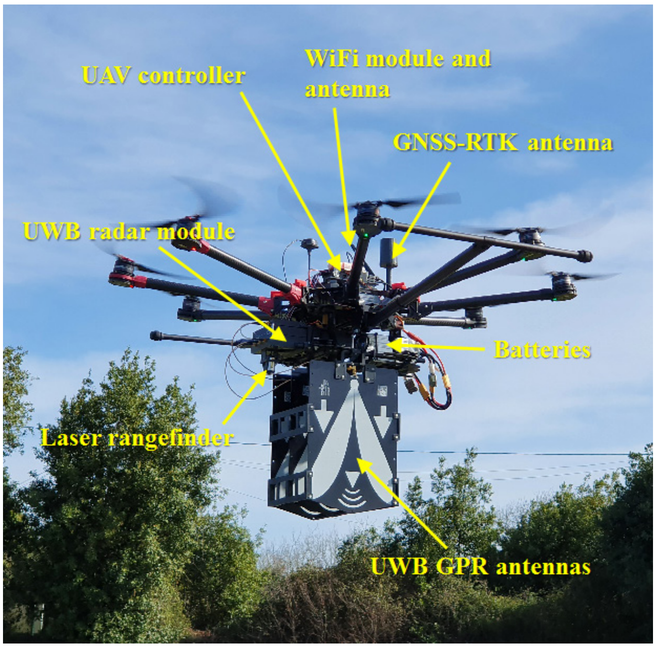

Fig. 1. Picture of the DL-GPR prototype.

As explained in [6], the radar has two receiving channels, thus allowing the use of two receiving UWB antennas. This allows improving spatial diversity (thus increasing dynamic range) by coherently combining the measurements of the two receiving channels. The antennas are one of the most important hardware components, having a significant impact on the performance of the system. Thus, different kind of UWB antennas have been tested throughout the project [10].

The geo-referring and positioning subsystem has been also improved compared to previous prototypes [6]. It consists of a triple-band multiconstellation GNSS-RTK receiver complemented with a laser rangefinder for accurate measurement of height above the ground. According to the manufacturer, the RTK accuracy is 1 cm in the vertical direction and 0.5 cm in the horizontal plane. Onboard UAV flight controller is connected to a micro-computer that, among other tasks, tags radar measurements with positioning information and send them to a ground station in real time. Communication between the UAV and the ground station relies on an ad-hoc Wireless Local Area Network (WLAN) in case of line-of-sight operation.

The scanning strategy is based on performing along-track sweeps following a zig-zag procedure, as illustrated in https://youtu.be/HDUwgka8Dns. Taking into account that the upper frequency limit considered for the GPR-SAR measurements processing is 3 GHz [6], across-track spacing between consecutive sweeps is set to 5 cm to fulfill the Nyquist sampling criterion. Even with a positioning uncertainty of ±1 cm, no aliasing effects are noticed in the GPR-SAR images.

B. *Advanced GPR-SAR processing techniques*

As indicated in Section II, several preprocessing techniques have been developed to tackle the challenges associated to UAV-based GPR systems. One of them is the strong clutter coming mainly from the air-ground interface, which can hinder the detection of shallow targets. Among other techniques, to deal with this issue, SVD filtering is applied to the GPR measurements [6],[11], so the SVD values associated to the eigenimages corresponding to the air-ground reflection are filtered out. Besides, gain processing has been introduced to improve the detectability of targets buried at certain depth [6] in moderate to high moisture soils.

GPR-SAR processing takes advantage of the fact that spacing between radar measurements is not greater than half a wavelength to create a synthetic aperture. However, in the case of UAV-based GPR systems, positioning uncertainties have an impact in SAR processing, limiting the maximum size of the synthetic aperture to be considered. For this reason, a technique called masked-SAR processing has been proposed. This technique consists of calculating the reflectivity at each voxel within the investigation domain considering only the acquisition points close to that voxel [6] (in particular, not further than $D_{ct} = 1$ m and $D_{at} = 2$ m in the cross-track and along-track directions, respectively) .

The flow-chart of the GPR-SAR processing and the pre and postprocessing techniques is shown in Fig. 2.

C. *Validation in a realistic scenario*

Validation of the implemented architectures in realistic scenarios, as close as possible to operational conditions that can be found in areas with high presence of IEDs and landmines, is the ultimate goal of the SAFEDRONE project. In this contribution, validation tests and detection results for the DL-GPR prototype are presented.

These tests were done at the Spanish Military Training and Shooting Range “El Palancar” (Hoyo de Manzanares, Madrid), in March 2021. The scenario was selected and prepared by the Counter IED Center of Excellence (C-IED CoE) and the Ministry of Defense of Spain.

Seven zones were defined within the scenario, each having a size of 4.5 m across-track and 12 m along-track, yielding around 380 m^2 in total. These zones were quite different in terms of roughness, slope, and moisture, so the performance of the UAV-based GPR prototype in different conditions could be properly assessed.

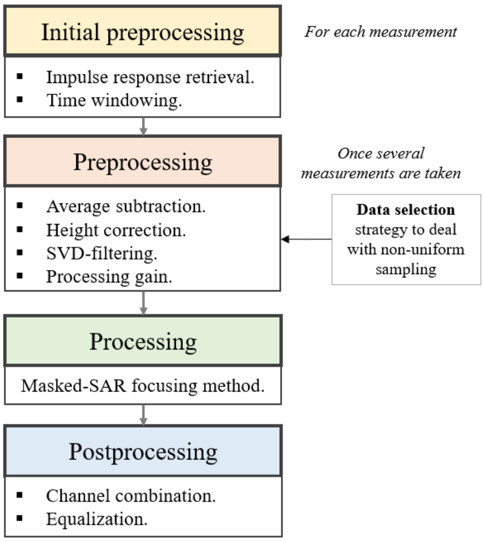

Fig. 2. Flow-chart of the radar data processing.

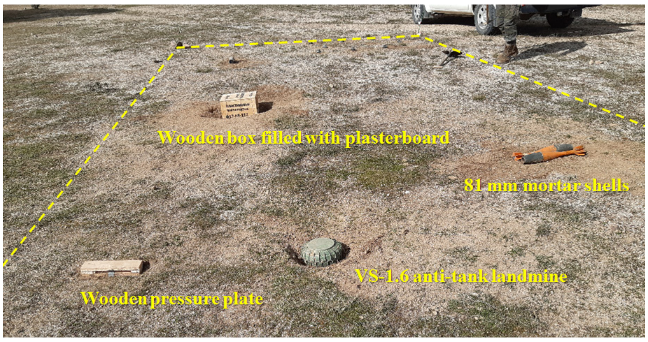

Fig. 3. Picture of scanned zone 2, with some of the targets uncovered.

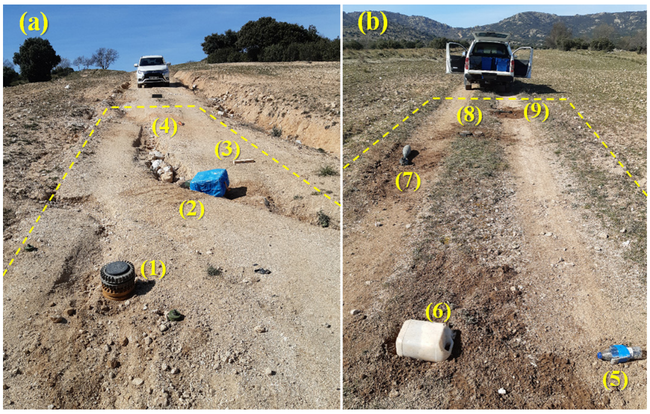

Fig. 4. Pictures of zones 5 (a) and 6 (b). Targets: (1) two stacked VS-1.6 antitank landmines, (2) wooden box filled with plasterboard, (3) wooden pressure plate, (4) 81 mm mortar shell, (5) plastic bottle acting as a pressure plate, (6) 25 litres plastic jug, (7) 120 mm mortar shell, (8) two VS-1.6 antitank landmines, and (9) two 81 mm mortar shells.

Up to 80 targets were buried, mainly consisting of IEDs, anti-tank and anti-personnel landmines, plastic jugs, pressure plates, mortar grenades, and artillery shells. Many of these targets were filled with explosive simulants or materials with similar constitutive parameters (e.g., plasterboard). Pictures of scanned zones no. 2, 5, and 6, together with some of the buried targets, are shown in Fig. 3 and Fig. 4.

An example of GPR-SAR imaging results for zone 2 is depicted in Fig. 5, which illustrates the dynamic range and the signal-to-clutter levels achieved with the implemented UAV-based DL-GPR prototype.

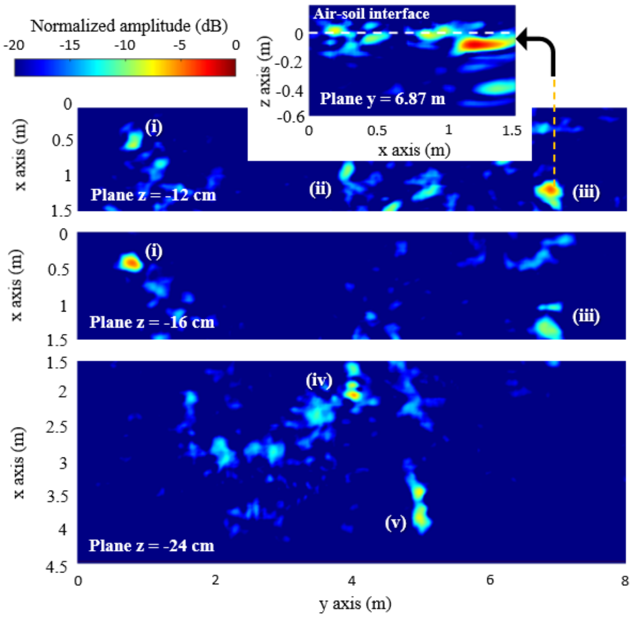

Fig. 5. GPR-SAR image of part of the zone 2. Detected targets: (i) plastic bag filled with papers, (ii) wooden pressure plate, (iii) wooden box, (iv) bottom side of the VS-1.6 antitank landmine, and (v) 81 mm mortar shells.

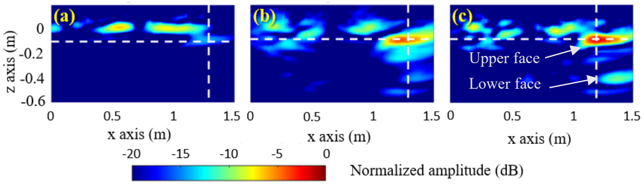

Fig. 6. GPR-SAR images (vertical cuts) of the wooden box target when no SVD filtering is applied (a), when no equalization is applied (b) and when both SVD filtering and equalization are applied (c).

In the case of the wooden box filled with plasterboard, reflections happening at both the upper and lower faces of the box are clearly detected (see vertical cut in Fig. 5, also depicted in Fig. 6c). However, if SVD filtering is not applied during the preprocessing (Fig. 6a), the box is hardly distinguished from the soil-surface interface. On the other hand, if equalization is not applied during the postprocessing (Fig. 6b), only the upper face can be detected. Therefore, the implemented pre and postprocessing techniques are essential to improve the detection capabilities.

In Fig. 7, the detection of 81 mm mortar shells in several zones (i.e., under different conditions) is compared. In zone 2 (flat and drier area), the two mortar shells are clearly detected.

In the dirt road area (zone 6), which is slightly wetter, they are also distinguishable, although the reflectivity level is smaller. Finally, in zone 5 (the steep dirt road, with very uneven ground surface), the mortar shell is also detected, although the contrast with the surrounding area is notably affected. Besides the terrain irregularities, in this zone only one mortar shell was buried, which also contributes to the deterioration of the detection capability.

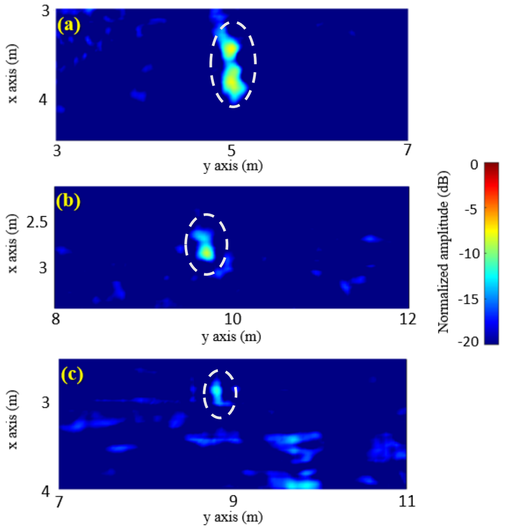

Fig. 7. GPR-SAR images (horizontal cuts) of the detection of 81 mm mortar shells in different zones: zone 2 (a), zone 6 (target (9) in Fig. 4) (b) and zone 5 (target (4) in Fig 4) (c).

It is worth noting that the detection capabilities have been tested following a blind procedure. This means that the location of the buried targets in the 7 scanned areas was not disclosed to the researchers that operated the prototype and processed the GPR-SAR images until they retrieved the detection maps of each area.

Detection performance showed a high probability of detection (>90%) of IEDs and any kind of buried targets whose size is larger than 10 cm, even when considering challenging operational conditions (steep dirt roads, very uneven ground, moisture areas, stony paths).

IV. HYBRID FL-DL-GPR ARCHITECTURE

FL-GPR architectures have been proved to be quite efficient to minimize the clutter coming from the air-ground interface. These architectures have been widely used in ground-based GPR systems for landmine and IED detection, as they also allow keeping a safety distance between the vehicle and the scanned area [12]. However, large free-space propagation losses together with non-specular reflection happening at the buried threats result in a poorer dynamic range if compared to DL-GPR architectures.

For this reason, a novel hybrid FL-DL-GPR architecture, initially proposed and simulated in [13], has been experimentally validated within the SAFEDRONE project. The goal of this architecture is to combine the advantages of FL-GPR and DL-GPR systems.

A picture of the implemented setup for on-ground validation is shown in Fig. 8. A radar system with independent Tx and Rx, operating in the 3-5 GHz frequency band, and capable of wireless synchronization, has been employed. This wireless synchronization is a key issue for further integration in the UAVs.

Using this configuration, the Tx is placed around 5 to 7 m away from the scanned area, pointing the Tx antenna toward the area to be scanned (i.e., following a FL-GPR configuration). The Rx antenna is pointed downwards to capture reflections in buried targets (DL-GPR). An additional antenna pointing towards the Tx module is connected to the Rx radar module to ensure a proper Tx-Rx wireless synchronization. Separation of the signals captured by the Tx-Rx synchronization antenna and by the Rx antenna pointing downwards is based on spatial filtering, using a delay line [14]. The rest of the payload elements depicted in Fig. 8 (microcontroller, RTK receiver, batteries) are the same as in the DL-GPR architecture.

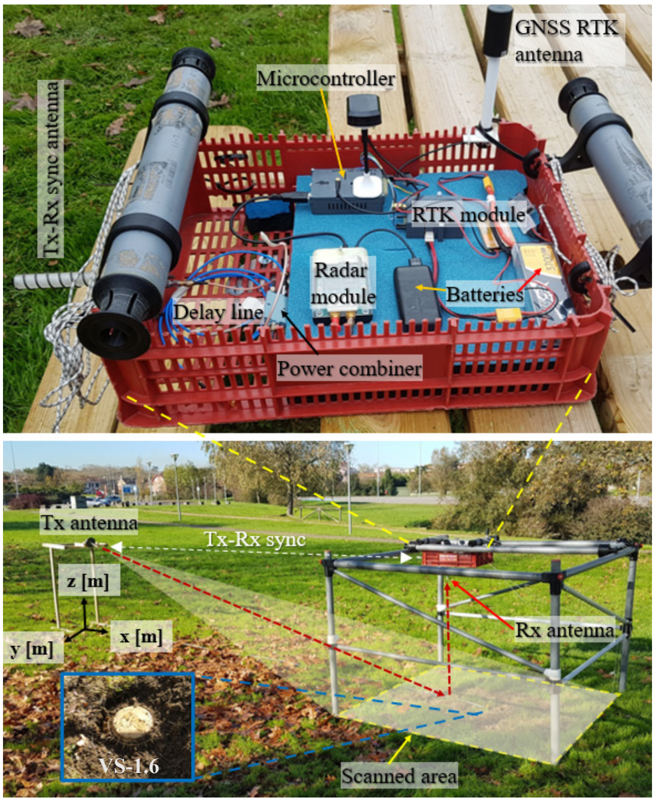

Fig. 8. Picture of the implemented FL-DL-GPR architecture, showing a detail of the Rx payload (upper picture). Lower picture: detail of the buried target, a VS-1.6 anti-tank landmine.

To validate the capability of the hybrid FL-DL-GPR architecture, a VS-1.6 anti-tank landmine has been shallowly buried. GPR-SAR imaging results obtained with the setup shown in Fig. 8 are plotted in Fig. 9. As it can be observed, not only the buried anti-tank landmine can be identified, but also the clutter associated to the air-ground reflection (that should appear at z = 0 m) is almost negligible.

Results of flights performed with this distributed architecture will be presented at the conference.

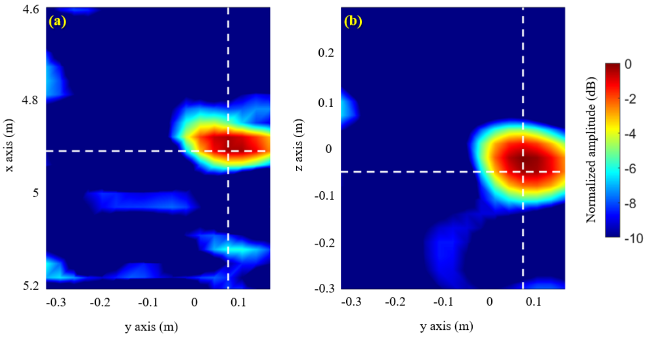

Fig. 9. GPR-SAR imaging results obtained with the FL-DL-GPR architecture. Buried target: plastic VS-1.6 anti-tank landmine. Horizontal cut (a) and vertical cut (b).

V. CONCLUSIONS

This contribution presents some of the achievements of the SAFEDRONE project, which is devoted to the development of high-resolution UAV-based GPR systems for buried landmine and IED detection. Concerning DL-GPR architecture, validation tests conducted in realistic scenarios showed a high probability of detection of targets whose size is larger than 10 cm, even when considering challenging operational conditions (steep dirt roads, very uneven ground).

Results for the hybrid FL-DL-GPR system also prove the effectiveness of this architecture to effectively minimize the air-ground interface clutter, showing its potential to detect shallow targets that could be missed by the DL-GPR system.

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Part of the SAFEDRONE subsystems have been implemented by the University of Vigo (contribution to the design of the antenna array) and by the company Inster Tecnología y Comunicaciones S.A.U. (beyond visual line-of-sight communications subsystem)

The technology presented in this contribution is protected by the patents listed in [15].

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