Validation of a UAV-mounted GPR system for landmine and IED detection under operational conditions

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ABSTRACT

In this contribution, the performance of a Ground Penetrating Radar (GPR) system mounted on board an Unmanned Aerial Vehicle (UAV) is analyzed. The ultimate goal of the system is to enable a safe, fast, and autonomous inspection of the subsoil to detect buried landmines and Improvised Explosive Devices (IEDs). Thanks to the integration of highly-accurate positioning sensors, the radar measurements are coherently combined using a Synthetic Aperture Radar (SAR) algorithm. Moreover, the SAR processing is complemented with several clutter mitigation techniques and, as a result, 3D high-resolution radar images of the subsurface with enhanced signal-to-clutter-ratio are retrieved. Several prototypes and different GPR architectures (conventional Down-Looking and distributed Forward-Looking/Down-Looking configurations) have been extensively tested in realistic scenarios (similar to operational conditions). In order to properly assess the detection capabilities of the prototypes, numerous metallic and non-metallic targets (antipersonnel and antitank landmines, and IEDs such as jugs and pressure plates) have been buried under different conditions (dry and wet fields, dirt roads, sloped terrains). The results of these experiments show that a high probability of detection can be achieved for targets with a diameter larger than 10 cm, either metallic or non-metallic, even under challenging operational conditions. In addition, analyzing the retrieved 3D radar images, it can be also concluded that the proposed clutter mitigation techniques are essential to achieve such high detection capabilities, especially when dealing with low-metal content devices. These techniques also allow to infer the shape of the buried targets, paving the way towards automatic target recognition.

Keywords: Ground Penetrating Radar, Unmanned Aerial Vehicle, Improvised Explosive Devices, Synthetic Aperture Radar

1. INTRODUCTION

In the last few years, there has been an increasing interest in integrating Ground Penetrating Radar (GPR) systems on board Unmanned Aerial Vehicles (UAVs).[1–3] Among their numerous applications, these UAV-mounted GPR systems are particularly useful for detecting buried landmines and Improvised Explosive Devices (IEDs), as they avoid the contact with the soil (thus guaranteeing safety conditions). The capacity of inspecting difficult-to-access areas, as well as the fact that GPR can detect both metallic and non-metallic targets, are also well-known advantages of these systems. In general, their main objective is to retrieve a high-resolution Synthetic Aperture Radar (SAR) image, where the concealed hazards can be detected. In order to enable SAR processing, these systems must also integrate high-accuracy positioning sensors.

In this field of application, SAFEDRONE project (Dec. 2019 - Jan. 2022) is one of the first R&D projects fully dedicated to enhance and demonstrate the performance of this kind of systems. In particular, the primary goals of the project were: i) improvement of detection capabilities (integration of advanced hardware and development of clutter reduction techniques); ii) development and comparison of several GPR architectures -conventional down-looking GPR (DLGPR), hybrid forward-looking/down-looking (FL/DLGPR) architecture, and DLGPR with an array of antennas; and iii) evaluation of the prototypes through extensive validation campaigns.

This contribution presents an overview of the DLGPR prototype, as well as some results obtained during the experimental validation campaigns performed in realistic scenarios.

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2. SYSTEM DESCRIPTION

The prototype of the DLGPR architecture is an evolution, in both hardware and software, of the previous prototypes developed by the research group.[3–6] As depicted in Fig. 1, the payload is composed by two main subsystems: the radiofrequency subsystem and the high-accuracy positioning subsystem. The radiofrequency subsystem comprises an Ultra-Wide-Band (UWB) radar working from 600 MHz to 6 GHz and three Vivaldi Antennas (one for transmitting and two for receiving, as there are two receiving ports in the radar module). The high-accuracy positioning subsystem includes a triple band multiconstellation Real Time Kinematic (RTK) receiver to provide cm-level accuracy positioning and a laser rangefinder to estimate the height to the soil surface.

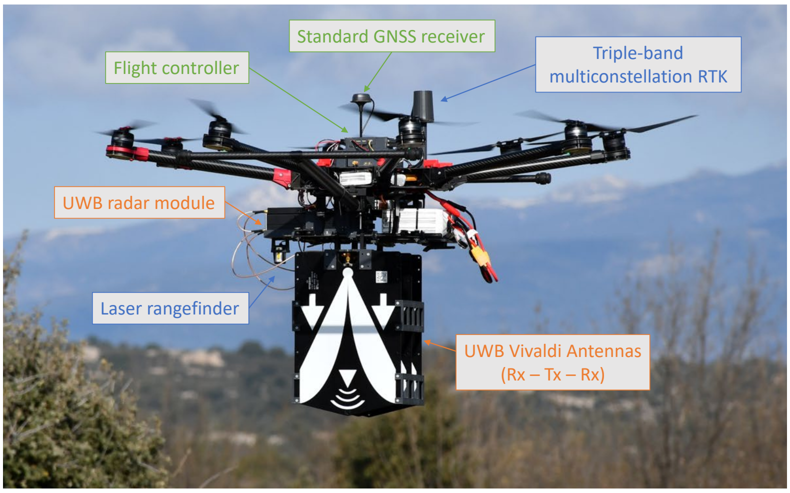


Figure 1. Photography of one of the prototypes during the validation trials, indicating their main components.

The prototype is configured to automatically fly over the area under inspection, following a rectangular grid (with the consecutive sweeps separated $\lambda_{3\mathrm{GHz}}/2 = 5$ cm). The radar measurements are geo-referred and sent in real time to the ground-control station. Then, the measurements are processed following the workflow depicted in Fig. 2, which is based on.[4,5] The core step of the methodology consists of coherently adding the radar measurements using a variation of the Delay and Sum algorithm called masked SAR. This algorithm is complemented with several pre- and post-processing techniques mainly devoted to mitigate the clutter, such as height correction and Singular Value Decomposition (SVD) filtering. It is also worth noting that one of the challenges of the system is related to the non-uniform acquisition of the data. Thus, subsampling strategies have been developed to compensate the non-uniform sampling and the deviations from the predefined flight path.

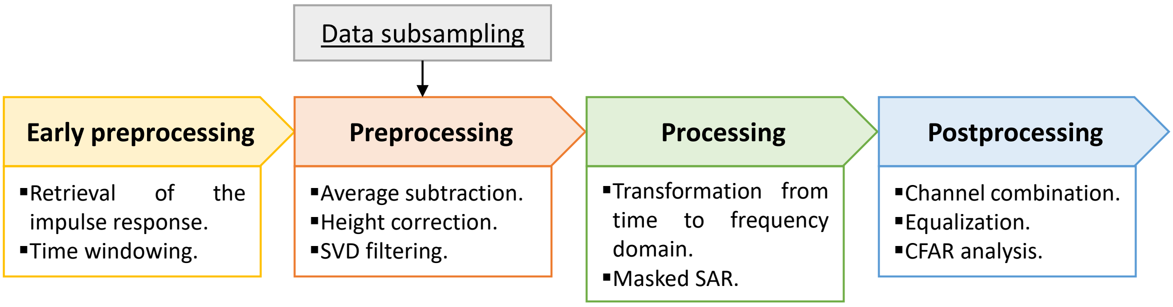


Figure 2. Processing workflow.

3. EXPERIMENTAL VALIDATION

Extensive validation campaigns have been conducted with the prototypes at the airfield of the University of Oviedo, and at the Spanish Military Training and Shooting Range “El Palancar”. The main goal was to assess the performance of the prototypes in realistic scenarios (resembling as close as possible to operational conditions).

Concerning the validation at the Military Training and Shooting Range, two major campaigns were conducted, composed of a total of 13 zones of $4.5\,\mathrm{m}\times 12\,\mathrm{m}$ (where more than 160 targets were buried). In order to analyze the performance under different conditions, these zones were significantly different from each other (from drier flat areas to steep dirt roads with very uneven ground). Furthermore, a wide range of targets have been considered, such as IEDs, anti-tank (AT) and anti-personnel (AP) landmines, pressure plates, and artillery shells, among others. It is worth noting that these validations campaigns (conducted in the framework of the SAFEDRONE project) followed a blind procedure (i.e., the research team did not know the location of the targets until the measurements were conducted and the detection maps of each area were obtained).

The radar image is reconstructed for each zone in a volume of $4.5\,\mathrm{m}\times 12\,\mathrm{m}\times 0.5\,\mathrm{m}$ (the considered height ranges from $+0.1\,\mathrm{m}$ over the ground to -0.4 m under the surface), discretized in voxels of $3\,\mathrm{cm}\times 3\,\mathrm{cm}\times$ 1cm size. Analyzing 3D SAR images is challenging, as it requires that the operator moves along the numerous horizontal (XY) and vertical (XZ and YZ) cuts of the 3D image. To facilitate the analysis, a Constant False Alarm Rate (CFAR) algorithm is applied to the horizontal cuts of the SAR image. This algorithm provides the coordinates of the voxels where there is a significant contrast with the surrounding voxels and, as a result, it is a likely that there is a target. Therefore, the operator knows which areas of the image should be carefully analyzed.

To illustrate the performance of the DLGPR prototype, the scenario shown in Fig. 3 has been selected. It is a flat dirt road, where four targets have been buried: a low metal content (LMC) AT landmine, an IED composed of a jug filled with fertilizer and a battery attached to it, a wooden pressure plate and two small submunitions. This zone has been selected as it mainly contains non-metallic targets.

Figure 3. Targets buried in one of the scenarios.

In Fig. 4 a composition of the detection results for this scenario is depicted, showing the detection map on top of a picture of the scenario. The detection map has been created by selecting the area around the targets in the horizontal cut where they are best detected, and next to each target its XY coordinates (on the left) and its estimated depth (on the right) are displayed. As shown in this figure, all the targets have been detected in this scenario, showing a significant contrast with the surrounding clutter.

In order to illustrate the effectiveness of some of the pre- and post-processing techniques developed, Fig. 5 shows the horizontal and vertical cuts of the GPR-SAR image centered at the jug’s top face. With a standard SAR processing, the target cannot be distinguished (Fig. 5a), although when two receiving channels are used it can be inferred (Fig. 5b). If masked SAR processing is applied (Fig. 5c), the target becomes more distinguishable, although there is still significant clutter. If the estimation of the UAV height above the soil surface is improved (Fig. 5d), the target is then clearly distinguishable. Furthermore, if SVD filtering is applied (Fig. 5e), the soil surface reflection is greatly reduced. Finally, when equalization is applied (Fig. 5f), the depth resolution is enhanced and the jug’s bottom face is also detected.

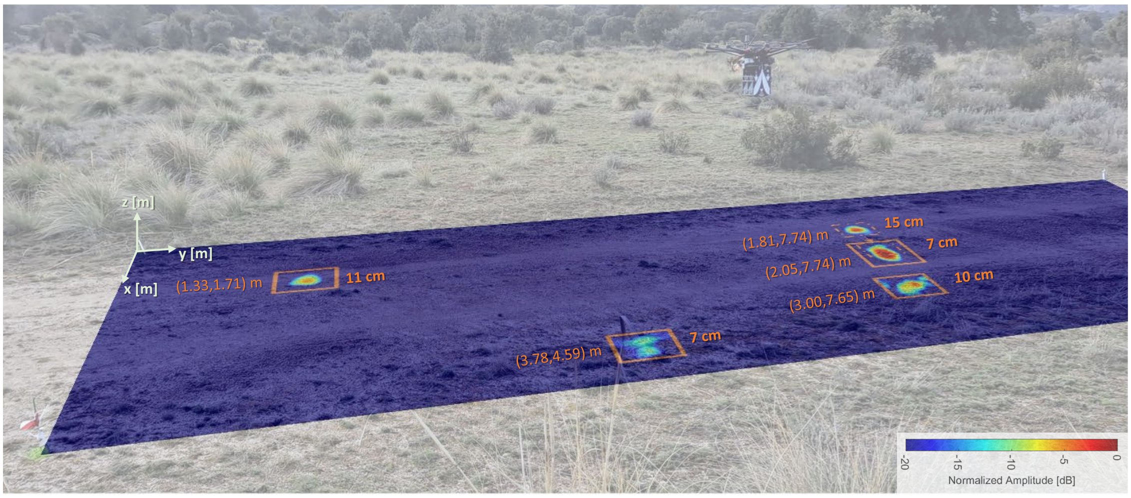
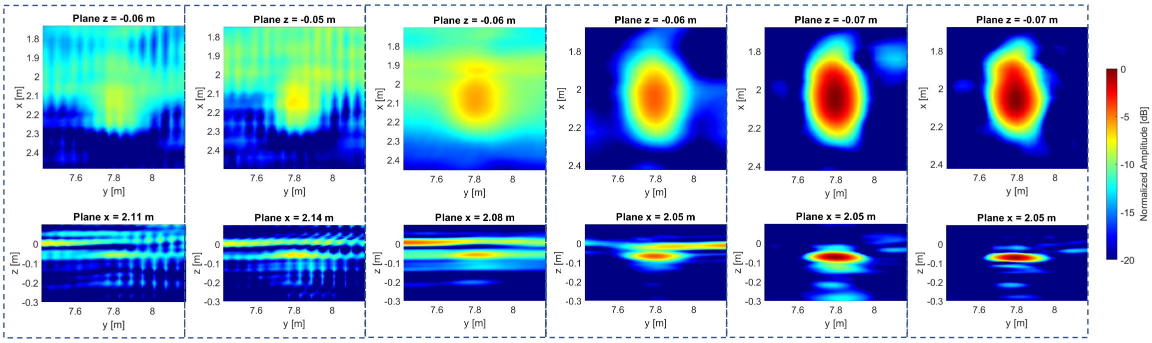


Figure 4. Detection map plotted on top of the scenario.



a) Standard SAR-processing 1 channel
b) Standard SAR processing 2 channels
c) Masked-SAR processing
d) Enhanced estimation of the height over the surface
e) SVD filtering
f) Equalization

Figure 5. Horizontal (top row) and vertical (bottom row) cuts of the GPR-SAR images of the jug's top face.

4. CONCLUSION

Results of the experimental validation campaigns in realistic conditions showed that a high probability of detection ($> 90\%$) can be achieved for targets with a diameter larger than 10 cm (metallic or non-metallic), even under challenging conditions (e.g., steep uneven dirt roads, with water runoffs). Furthermore, the results shown in this contribution demonstrate that 3D high-resolution GPR-SAR images with a good signal-to-clutter level can be retrieved from UAV-mounted GPR systems, provided appropriate clutter removal techniques are applied.

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