Development of a cm-resolution ground penetrating UAV-SAR system for 3D subsurface radar imaging

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Abstract

Innovative synthetic aperture radar concepts for close-range high-resolution applications have been enabled by the rapid developments in unmanned aerial vehicles in recent years. In combination with highly integrated ground penetrating radar, such systems provide a basis for new sensing solutions in many applications. At DLR, a radar sensor called DRONAR using 100 % relative bandwidth at a center frequency of 2 GHz is developed and serves as payload for an off-the-shelf multi-copter platform in order to demonstrate this novel technology. Unique three-dimensional subsurface imaging capabilities of this sensor are demonstrated using an experimental dataset acquired in October 2023. Recent developments of the system and the validation of the 3D imaging performance is presented in this contribution.

1 Introduction

The combination of unmanned aerial vehicles (UAV) as versatile platforms with highly integrated, lightweight radar sensors allows for unique synthetic aperture radar (SAR) imaging concepts in near-range high-resolution applications. Further advantages of such sensor systems are the cost-efficiency of SAR acquisitions, the possibility for multi-static systems and swarm operations, and the arbitrary revisiting times for change detection of time variant observables. Technological challenges such as motion errors, operational times and efficient antenna designs remain, but due to the manifold advantages and possibilities, there is an increasing research interest in such sensor systems [1]. Additionally, radar sensors at low carrier frequencies and high relative bandwidths allow for operation of a ground penetrating SAR sensor with resolutions in the centimeter range. The areas of application for such systems are diverse as shown in [2]. They include but are not limited to buried object detection [3], local-scale soil moisture retrieval [4] and glaciology [5]. Besides of high-resolution SAR images, the high flexibility of the UAV platforms allows for multi-baseline acquisitions, e.g. linear apertures at multiple altitudes, multi-circular or even helical trajectories. Thereby, various different incidence angles span a synthetic aperture in vertical direction and enable 3D SAR imaging of subsurface scatterers [6]. Thus, detection and identification capabilities of such a sensor can be further increased and the retrieved information can be used as a first step towards automated object identification, circumventing the complexity and cost of interpreting SAR images by human operators.

In this paper the recent developments at DLR towards DRONAR, a ground penetrating UAV-SAR sensor based on a stepped-frequency continuous wave (SFCW) radar for 3D subsurface imaging, is presented in detail. The RF hardware and its design parameters are described and experimental results obtained with the system are shown, which demonstrate the 3D imaging capabilities of our system.

Figure 1: Photograph of the UAV-SAR sensor system

2 UAV-SAR Sensor DRONAR

Starting around 2018, the radar system is designed as a stepped-frequency continuous wave (SFCW) radar similar to the approach in [7]. In contrast to this design, a homodyne SFCW receiver is implemented to reduce the complexity of the RF circuitry. The generated signal is transmitted and received using two separate commercial quad ridged horn antennas [8]. This new design brings the advantage of a further simplified RF design and reduced weight due to the missing circulator in the receiving path.

Table 1: Radar system parameters

Parameter	Value
Center frequency	2 GHz
Bandwidth	2 GHz
Waveform	SFCW
Transmit power	+15 dBm
Pulse repetition frequency	80 Hz

Figure 2: Experimental setup with a) metallic reference targets and metallic spheres with b) 30 cm, c) 20 cm, d) 15 cm and e) 12 cm diameter. The spheres are buried such that the minimum depth between spheres and surface is 5 cm.

A separate power supply based on Lithium polymer batteries is used for the radar system. Thus, the operational time of the sensor system is increased since the UAV batteries are not used for radar operation. Furthermore, the radar supply voltages can be efficiently conditioned, such that no ripples impact with the overall radar performance. At the moment, position tracking of the UAV is performed by a laser-based tracking system consisting of a total station on ground, which tracks the position of an optical prism mounted at the UAV [9]. As an UAV platform, a commercial off-the-shelf multi-copter is used [10]. The sensor parameters are summarized in Table 1 and a photograph of the system is shown in Figure 1.

3 Experimental Setup

An experimental campaign to evaluate the performance of the presented UAV-SAR sensor has been performed in October 2023 at DLR in Oberpfaffenhofen. The test site is shown in Figure 2. It consists of 4 metallic reference targets placed at the surface of a flat well-controlled sandbox environment. The reference reflectors are located at the vertices of a square with side length of 4 m, which marks the measurement area. Inside this area, four metallic spheres with different diameters were located. The diameters were chosen as 30 cm, 20 cm, 15 cm and 12 cm. To demonstrate the subsurface imaging capabilities of the system, the spheres where buried, such that the minimum depth between the sphere surfaces and the sand surface was 5 cm. Seven linear flight tracks in different altitudes were performed and serve as basis for the generation of a three-dimensional SAR product. The flight altitude was increased linearly from 4 m to a maximum altitude of 8 m. The position data acquired with the laser-based tracking system is visualized in Figure 3. SAR processing is performed using the well-known backprojection algorithm [6] to form a three-dimensional image within the measurement volume indicated as well in Figure 3.

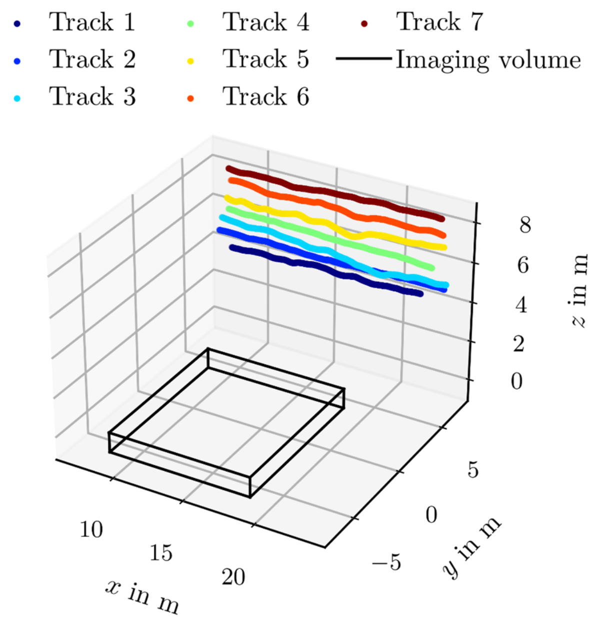

Figure 3: SAR imaging geometry

After the processing of the individual tracks, all images are coherently combined to form the final three-dimensional data product. Figure 4 shows a section through the x-z-plane at the position of the buried spheres b and c from Figure 2. It can be recognized that the metallic spheres clearly separate from the surrounding clutter background, which can allow the application of automated target detection and possibly recognition algorithms. Hence, the 3D focusing of the radar raw data behaves as expected and thus the sensor performance could be demonstrated.

4 Conclusion

The 3D subsurface imaging capabilities of the developed ground penetrating UAV-SAR sensor DRONAR have been demonstrated experimentally. Next steps include a further analysis of the imaging performance as well as the development towards a polarimetric sensor system.

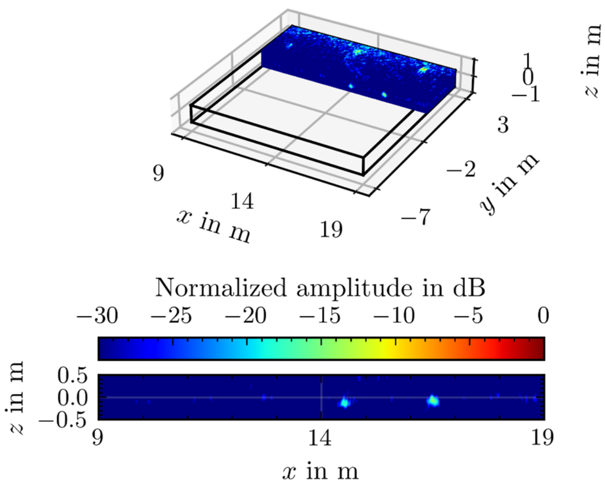

Figure 4: Section through the x-z plane of the imaging volume at the y position of the spheres b and c.

5 Literature

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