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Comparison of subsampling strategies for UAV-mounted subsurface radar imaging systems

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***Abstract*—This paper compares two subsampling strategies for UAV-mounted subsurface radar imaging systems, which feature non-uniform acquisitions that have an impact on the quality of the resulting radar image. The first method is based on selecting those samples that meet four conditions related to the UAV flight speed and stability. In contrast, the second relies on dividing the observation domain in a grid of cells, and selecting only a maximum of a given number of samples within each cell. The impact of both techniques on the image quality is assessed by means of measurements.**

I. Introduction

In the last few years, radar imaging systems on board Unmanned Aerial Vehicles (UAVs) have become a trending research topic [1]–[3]. In particular, innovative applications of these systems for Non-Destructive-Testing (NDT) have been proposed, thanks to their ability to autonomously inspect difficult-to-access areas without interacting with the surroundings. Among these applications, a great research effort has been directed towards developing Ground Penetrating Radar (GPR) systems on board UAVs for the detection of landmines and Improvised Explosive Devices (IEDs). The ultimate goal of UAV-mounted GPR systems is to obtain high-resolution subsurface radar images, where buried targets can be detected. This is enabled by coherently combining the radar measurements using Synthetic Aperture Radar (SAR) techniques [3].

One of the main challenges arising in this kind of systems is related to the difficulty of performing a uniform acquisition [4]. Although UAVs can be programmed to follow a uniform flight path (e.g., a rectangular grid), flight deviations from the predefined flight path occur due to internal disturbances (such as unmodeled effects in the control system and positioning uncertainties), and external perturbations (such as wind-gusts). Furthermore, the UAV speed is likely to change along the path. This non-uniform speed yields to non-uniform sampling of the radar measurements. Therefore, the data processing techniques must deal with non-uniform sampling and deviations from the ideal flight path. In particular, the adopted SAR technique must be able to work with radar measurements gathered at arbitrary positions, and a subsampling strategy must be defined to select the subset of measurements that will be processed.

II. System Description

The UAV-mounted GPR prototype [4], [5] is shown in Fig. 1. It comprises a radar working from 600 MHz to 6 GHz and a highly accurate positioning system, composed by a Real Time Kinematic (RTK) receiver and a laser rangefinder. The prototype is configured to autonomously follow a predefined flight path, sending the geo-referred radar measurements to a ground control station in real time. These measurements are processed to retrieve a 3D radar image using a SAR algorithm.

Fig. 1. Image of the UAV-mounted GPR system during the test flight.

III. Methodology

In UAV-mounted systems it is particularly difficult to perform uniform acquisitions. Therefore, a subsampling technique to select which measurements will be processed must be developed. Its main goal is to ensure that the selected subset resembles as close as possible a uniformly sampled acquisition. Therefore, it must discard those samples which could degrade the image quality (avoiding oversampled areas and compensating flight path deviations). Two strategies are compared: one is based on keeping the samples that fulfill several conditions (related to speed and flight stability), and the other is based on dividing the observation domain in cells (selecting only a given number of samples per cell).

A. Subsampling strategy based on conditions

This subsampling strategy, which is an improvement of [6], establishes four conditions that the samples must meet in order to be selected for processing: a speed condition (to avoid oversampled areas, which in turn correspond to measurements at low speeds), and other three related to flight stability (discarding samples when the attitude, ground track or height of the UAV are far from the desired ones). The speed condition is $v_{gr} > th_v$ (where v_{gr} is the UAV ground speed, and the threshold th_v is estimated from the histogram of v_{gr}), and the remaining conditions are further explained in [5].

B. Subsampling strategy based on cells

The cell-based subsampling technique has been proposed in [7], [8] for freehand systems. It relies on dividing the observation domain in cells, selecting only N_s measurements per cell. If more than N_s samples fall within a cell, these additional samples will be discarded. For this system, a cell size of $\lambda/2$ has been selected, and N_s has been set to 1.

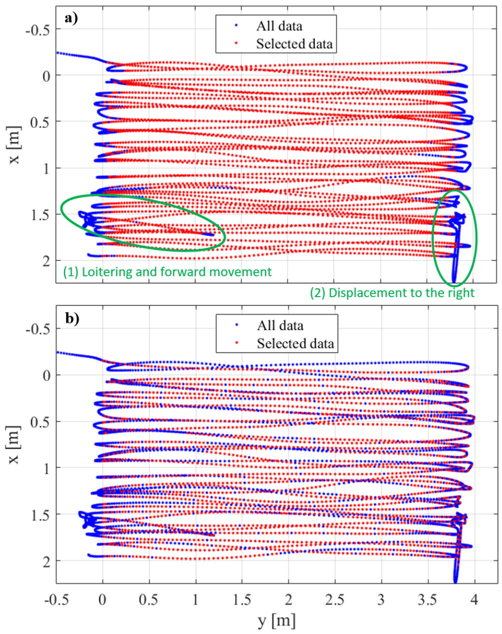

Fig. 2. Positions of all measurements in blue and the selected ones in red (for the condition-based criteria in a) and for the cell-based criteria in b).

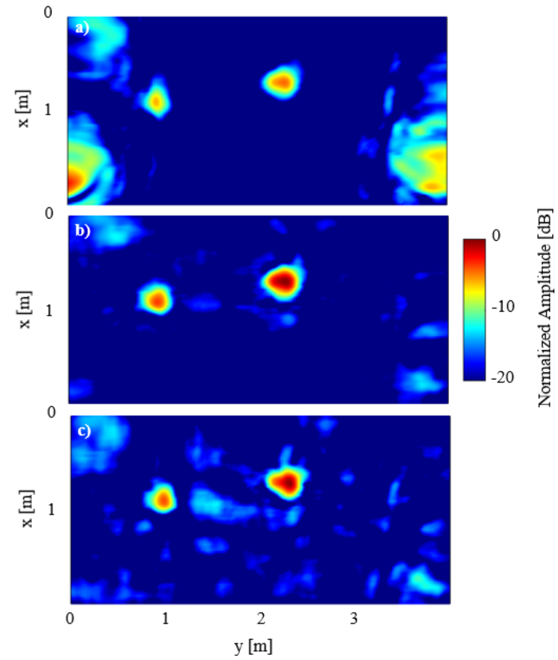

Fig. 3. Horizontal cut of the radar image at $z = -13\,\text{cm}$ when: all measurements are considered (a), when the condition-based criterion is used (b) and when the cell-based criterion is adopted (c).

IV. Experimental Validation

In order to assess the performance of the proposed techniques a test flight was conducted in a military training and shooting range within the framework of an extensive validation campaign of the UAV-mounted GPR system (see Fig. 1). For testing the impact of the subsampling strategies in the radar image quality, two metallic targets were buried at 13 cm depth.

The test flight consisted of a predefined rectangular grid path of $2\,\text{m}\times 4\,\text{m}$, with a separation between consecutive sweeps of 5 cm. The autonomous flight was interrupted twice, then controlling manually the UAV flight for a short period of time to simulate harder non-uniform conditions (highlighted in green in Fig. 2). The positions of all measurements are shown with blue dots in Fig. 2, whereas the selected positions are depicted in red. The first criterion selects 52.94% of the measurements, whereas the second one only selects 34.02%.

The 3D SAR radar images have been computed considering all measurements as well as the subsets selected by each subsampling technique. In Fig. 3, the horizontal cuts at the depth where the targets were buried are compared. When all measurements are processed there is a high level of clutter (especially where the interruptions were forced). However, when the subsampling techniques are applied, these highly cluttered areas disappear, and the signal to clutter ratio is improved. The first technique yields a slightly better image quality, but it requires more computational time (as more measurements are selected).

V. Conclusion

The adoption of a subsampling strategy is essential to retrieve high quality radar images in UAV-mounted GPR systems. Furthermore, it also helps to reduce the computational time (discarding measurements that do not add valuable information). Two subsampling strategies have been compared, concluding that signal to clutter ratio is slightly better for the condition-based criterion, whereas the computational time is significantly smaller for the cell-based one.

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