A Micro-UAV-borne system for radar imaging: a feasibility study

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Abstract— **Radar mounted onboard micro-UAV is an early stage technology and its potentiality is far from being focused, even if radar sensors having costs compatible with micro-UAV are currently developed. As a contribution to this topic, this paper describes a radar-equipped hexacopter assembled thanks to complementary skills available at IREA and DII. In order to test the operation mode of the system as well as to investigate its target detection and localization capabilities, a feasibility experiment has been carried out in December 2016. The results of this flight campaign are presented, in terms of both raw data and images obtained by means of an ad-hoc data processing approach. These results provide an encouraging preliminary proof of the achievable outcomes.**

Keywords—UAV system; radar survay; imaging; data processing.

I. INTRODUCTION

In recent years, Unmanned Aircraft Vehicles (UAV) have proven their value in a wide range of applications. Besides being used in the military sector, UAV are becoming popular for addressing many significant missions such as border protection, coastal surveillance and crime fighting, hurricane and polar ice cap monitoring, forest fire detection, natural disasters response, aerial photography, crop dusting, news organizations, package delivery, and pipeline and power line monitoring [1]. Miniaturization of flight control systems and payloads also contributed to an increasing diffusion of micro-UAV, both in fixed wing and rotary wing configurations [2].

Micro-UAV can be a powerful tool in several application fields and systems equipped with optical cameras are available on the market at an affordable cost. Indeed, UAV-based optical photogrammetry and infrared imaging are quite assessed and wide spread adopted technologies (there are several examples pointing out their utility in disaster rescue and management, in forestry and agriculture, in archeology and architecture [3]).

On the other hand, exploiting the full potential of micro-UAV for societal benefits requires an improvement of their sensing capability, beyond the realm of active/passive optical sensors and daylight/infrared cameras.

In this frame, radar systems are gaining attention since they are capable of performing missions in all-weather and day/night conditions and, thanks to the ability of microwaves to penetrate materials, they allow detection and localization not only of surface objects but also of subsurface/hidden targets.

However, micro-UAV borne radar imaging represents still a new frontier. Indeed, although airplane or helicopter mounted radars have been considered for surface and subsurface surveys and tomographic approaches have been proposed to image hidden targets [4], at present, radars onboard UAVs are limited to medium/large platforms with significant mass, size, power and cost budgets.

Micro-UAV radar imaging is, indeed, much more than a matter of technology miniaturization or payload installation, which can take advantage of the newly developed ultra-light system. Specifically, Micro-UAV radar imaging entails scientific challenges in terms of electromagnetic modeling and flight dynamics knowledge and control. For instance, ad-hoc and sophisticated data processing approaches are demanded to compensate for the limited performance of small, lightweight platforms and acquisition systems. Therefore, despite Synthetic Aperture Radar (SAR) imaging is an assessed remote sensing tool, its adaption to micro-UAV is an open issue and few examples concerning the integration of SAR and UAV technologies have been reported world-wide [5]. In addition, only very preliminary results concerning subsurface imaging via UAV mounted radar have been provided [6].

As a contribution to radar surveys by means of micro-UAV, we are working on a general methodological approach that, by exploiting radar imaging and avionics skills, aims at designing a flexible UAV-based radar system capable of providing high resolution images of the scenarios under test.

To pursue this goal, we take advantage of currently available or easily customizable radar systems, whose mass, size, power and cost budgets are compatible with installation on small micro-UAV. Moreover, we exploit suitable data processing approaches to improve target detection and localization capabilities. On the other hand, we aim at developing guidance, navigation and control (GNC) approaches based on low cost MEMS-based (Micro-Electro-Mechanical Systems) avionics to increase flight stability.

This paper deals with the first considered open issue, i.e. making a first feasibility study about the imaging/detection performance, which is achievable by using a low power miniaturized UAV-borne radar system driven manually by an expert user.

To address this issue, a proof-of-concept experiment has been carried out and it is herein reported. The experiment has been performed by using a single radar-equipped drone, made

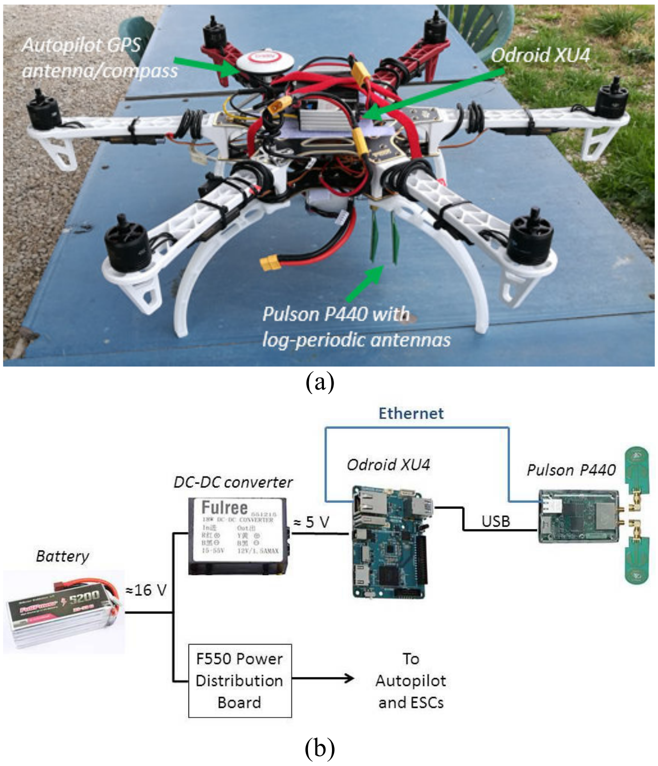


Fig.1: Radar equipped UAV: a) picture of the system; b) Payload hardware architecture

by an ultra-light commercial radar system mounted on a hexacopter.

This communication is organized as follows. Section II deals with the system description, while the experiment is detailed in Section III. The adopted data processing approaches are summarized in Section IV together with an example assessing the achievable imaging capability. Conclusion and future work are outlined in Section V.

II. RADAR-EQUIPPED UAV SYSTEM

The radar-equipped UAV system is shown in Fig.1a. As it is detailed in the following subsections, the system is made by a flexible hexacopter and an ultra-light radar. The radar is connected through an Ethernet link to a miniaturized computer mounted onboard the UAV and controlled automatically.

A. UAV system

The micro UAV adopted for flight tests is a self-assembled DJI F550 hexacopter, available at DII. The F550 represents a flexible platform that can embark several auxiliary onboard systems up to a maximum payload weight close to 1 Kg.

In the configuration adopted for radar acquisition flights, it was controlled by means of a DJI Naza M-Lite autopilot (installed in the hexacopter center of mass) complemented by a remote GPS/compass installed on a mast. The autopilot enables different levels of remote control, such as manual, attitude stabilized mode, and GPS/attitude mode.

The systems was deployed in the last mode thus receiving commands in terms of climb rate, yaw rate, and velocity components in the horizontal directions.

The onboard payload for the radar sensing test includes the radar system, which is described in the next subsection, an Odroid XU4 computer and a DC-DC converter. The radar has been installed near the battery below the center plate of the F550 frame, in order to minimize obstructions and disturbances to/from the other electronics components. Odroid and DC-DC converter have been installed above the plate.

In order to minimize payload weight, no auxiliary batteries have been installed. Instead, the Odroid XU4 has been powered by adding a custom Y connection between the F550 battery and its power distribution board. Since the battery voltage is of the order of 16 V, a lightweight DC-DC converter has been added to convert the voltage to 5V as needed by the Odroid. The radar has been powered by a USB port of the computer, while radar data have been exchanged via an Ethernet link. This installation choice does not impact in significant way the flight autonomy, due to the very small power required by the computer (and the radar). In terms of software, the XU4 runs a Linux-based operating system. The payload hardware architecture is depicted in Fig.1b.

B. Radar system

As radar we have used the commercial PulsON 440 system [7], which is available at IREA. This radar is a short-range, time domain, ultra wideband system that has been chosen because of its compactness, low cost and low power. The sizes, indeed, are 56 mm x 103 mm x 18 mm, while the weight of the radar is about 100 grams. A picture of the radar is shown in Fig.1b.

The radar is equipped with Serial, USB and Ethernet connections and can be commanded by using a Graphical User Interface or by means of open source codes. Once mounted onboard the UAV system, the radar is controlled by using the data acquisition software (written in C language), which has been developed by properly customizing radar support software provided by Pulson. The software has been launched remotely using the SSH tool available in Linux. Hence, the radar works in free-running mode.

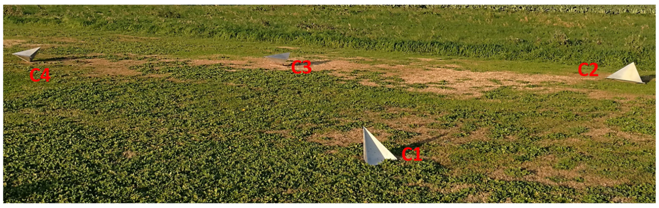
The radar allows quasi-monostatic measurements by using two antennas, one transmitting and the other one receiving, which are close in terms of radiated wavelength. Instead of default antennas, which are shown in Fig.1b, we have equipped the radar with small size log-periodic PCB antennas. In particular, Ramsey LPY26 have been used as transmitting and receiving antennas. These are directive antennas having a 6 dB gain over the frequency range from 2 GHz to 11 GHz. The antennas have been mounted in a down looking configuration (see Fig. 1a).

The radar has been programmed in such a way to acquire 10 waveforms for second.

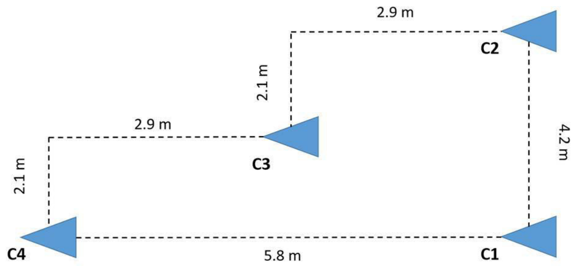
III. EXPERIMENTAL TEST

A proof-of-concept experiment was carried out the 22nd December 2016 at an authorized site for UAV flights driven by amateur users. The experiment was performed in a cloudy evening with soft wind conditions.

The main aim of the experiment was to test the ability of the assembled system to gather useful data. Therefore, it allowed a preliminary assessment of the achievable imaging capabilities.



(a)



(b)

Fig.2: target arrangement: a) picture; b) sketch

Accordingly, as usually done for a proof-of-concept experiment, corner reflectors have been used as targets, since they behave as strong scattering objects.

In particular, four corner reflectors were located on the surface of the test site as shown in Figs. 2a, b. These figures provide a picture and a sketch of the corner positions, respectively. Moreover, Fig. 2b gives details on the spatial offsets between the targets.

For this preliminary experiment, we did not use advanced techniques for accurate UAV navigation, such as differential GPS or visual odometry. An expert user remotely piloted the micro-UAV. Conversely, the radar was controlled automatically by using an ad-hoc developed data acquisition software installed on the miniaturized computer mounted onboard of the UAV system, as said in the previous Section. In particular, we planned to gather data in a measurement slow time range of 180 s and we set the observation fast time window from 16.67 ns to 81.12 ns.

The data acquisition test was successfully completed and Fig. 3 shows the overall raw data collected during the flight, when the UAV system made two round trip travels on the flight field by moving with a variable velocity.

It is worth noting that several diffraction hyperbolas are visible in Fig.3, which are indicated by red arrows. They represent the corner reflectors as seen by the radar provided that the round trip movement with a non-constant velocity of the UAV is taken into account. Moreover, not negligible undesired signals overlap the useful ones.

To test the accuracy of the target localization, more precisely the possibility of obtaining a focused image, we applied the data processing procedures summarized in the next Section to a portion of the radargram in Fig. 3, wherein only one hyperbola, corresponding to one of the target, appears.

IV. Data processing

First of all, we select the portion of the radargram to be considered by selecting the portion of the measurement time range as well as the portion of the observation time window.

As a second step, we apply time gating [8] in order to force to zero the portion of the radargram corresponding to antenna

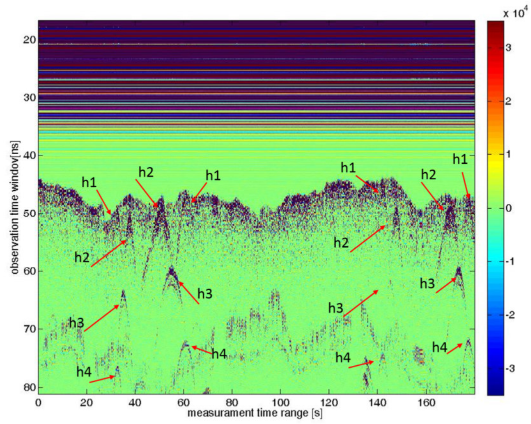


Fig.3: Overall collected radargram, where the diffraction hyperbolas of interest are denoted by means of red arrows.

direct coupling and the undesired signals occurring in time window from about 16ns to 40 ns.

As a third step, we take advantage of a Singular Value Decomposition (SVD) procedure to reduce noise. This procedure requires the computation of the SVD of the data matrix obtained after applying the time gating. In particular, let **A** be this matrix, it is represented by means of its SVD as:

$$\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^T = \sum_{i=1}^{Q} \sigma_i \mathbf{u}_i \mathbf{v}_i^T \qquad (1)$$

where **U** e **V** are orthogonal matrices having size $N \times N$ and $M \times M$, respectively; **S** is the $N \times M$ diagonal matrix whose elements are the singular values of **A** arranged in a decreasing order of magnitude and $Q \leq min\{M, N\}$ is the rank of **A** [9]. N represents the measured waveforms, while M denotes the time sampling points used to represent each waveforms.

The noise filtered data matrix is obtained as:

$$\tilde{\mathbf{A}} = \mathbf{A} - \sum_{i=P}^{Q} \sigma_i \mathbf{u}_i \mathbf{v}_i^T \qquad (2)$$

The threshold P is chosen as the index of the singular value in correspondence of the point where the spectrum changes its slope, i.e. the index of the singular value where the fast decay of the singular values is followed by the smooth one. According to eq. (2), we are assuming that all the singular values whose amplitude, as normalized to the maximum one, is lower than a fixed threshold are representative of the undesired portion of the measured signal.

As a fourth and final step, we compute the spectrum of the data matrix $\tilde{\mathbf{A}}$ and process the so obtained frequency domain data by means of a linear microwave tomographic approach. This latter uses the canonical 2D free space model and the Born Approximation to describe the underlying scattering phenomenon [10].

The above summarized procedures have been used to process the portion of the radargram corresponding to the measurement time range from 55 s to 65 s and the observation time window from 20 ns to 58 ns. This radargram portion

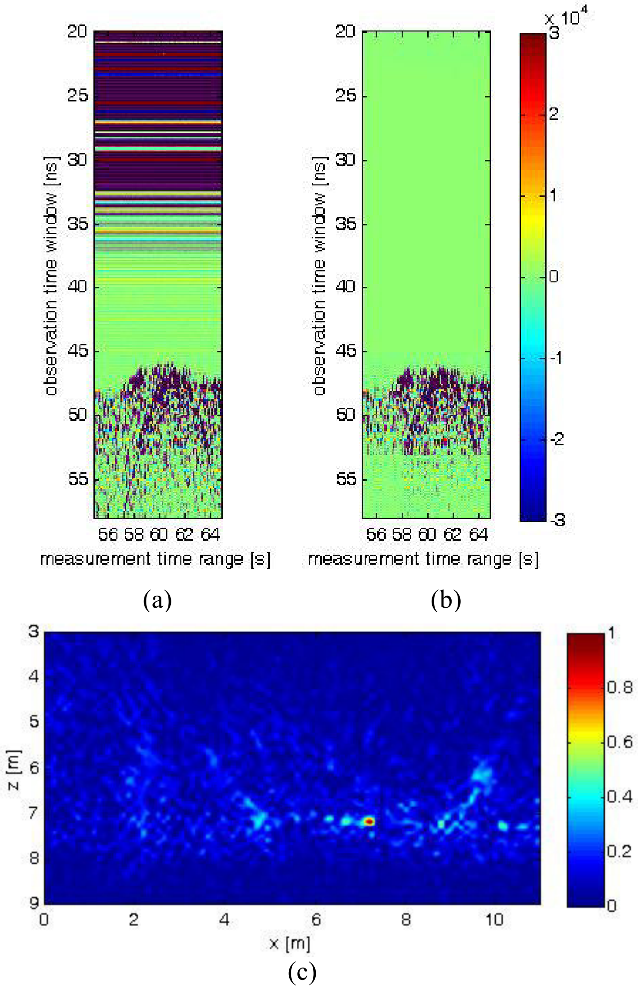


Fig.4: Imaging capabilities assessment: a) portion of the radargram of interest; b) time gated and noise filtered data; c) tomographic reconstruction.

contains the hyperbola representing the backscattering signal due to the corner reflector C4 (see Fig. 2).

Figures 4a-c show the selected portion of the radargram, the time gated and noise filtered data as well as the tomographic image, respectively.

The time gated and noise filtered data have been obtained by setting the time gating at 45 ns and the threshold *P* as the index of the singular value whose amplitude is 0.3 time lower than the maximum one.

The tomographic image has been obtained by taking into account that data corresponding to the selected portion of the radargram were acquired by moving the UAV with an estimated velocity of 1.1 m/s. Hence, since the radar acquired 10 waveforms for second, we considered a measurement line 11 m long and 101 evenly spaced measurement points. Moreover, we set the useful frequency range from 3.4 GHz to 4.6 GHz and we sampled it by using a frequency step equal to 20 MHz, i.e. we used 61 evenly spaced frequencies. Finally, we chose as investigated domain a rectangle, whose side was 11 m along the flight trajectory (i.e. the x axis) and 6 m along the range direction (i.e., the z axis). Specifically we set z_{min} = 3m and z_{max} = 9m. The investigated domain was sampled into 6161 pixels whose side is 0.11 m.

By comparing Fig. 4a and Fig. 4b, we can observe that time gating and SVD based procedure allow us to reduce the undesired signals. Moreover, Fig. 4c corroborates that the microwave tomography approach provides a focused image from which the location and size of the target are retrieved.

V. Conclusions

UAV-mounted radar systems are a leading edge technology for surface and subsurface imaging and several open issues have to be addressed, among which automatic radar control, ability to obtain focused images and GNC procedures for autonomous flights.

In this paper, we have described a system recently assembled thanks to the cooperation between the IREA and DII researchers and described a preliminary experiment devoted to assess that the system works and collect data properly. Moreover, data processing approaches have been summarized and their usefulness assessed by processing a portion of the overall collected radargram. In particular, the capability of obtaining a focused image allowing an accurate target localization has been proved.

This encouraging preliminary result motivates to go on with the research activity, which will regard, first of all, the integration of advanced GNC techniques in order to carry out autonomous flights and accurately estimate position and attitude of the UAV along its trajectory.

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