77 GHz Radar-Based Altimeter for Unmanned Aerial Vehicles

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***Abstract*— For multi-copter unmanned aerial vehicles (UAVs) sensing of the actual altitude is an important task. Many functions providing increased flight safety and easy maneuverability rely on altitude data. Commonly used sensors provide the altitude only relative to the starting position, or are limited in range and/or resolution. With the 77 GHz FMCW radar-based altimeter presented in this paper not only the actual altitude over ground but also obstacles such as trees and bushes can be detected. The capability of this solution is verified by measurements over different terrain and vegetation.**

***Index Terms*— Radar, unmanned aerial vehicles, altimetry, chirp modulation**

I. Introduction

In state-of-the-art consumer UAVs a variety of sensors are installed. The flight controller stabilizes the aircraft with the help of the internal measurement unit (IMU) including a 3-axis gyroscope and an accelerometer. For altitude sensing barometric pressure sensors and a global positioning system (GPS) are used. Using GPS, these drones can also fly to waypoints in an autopilot mode. However, both sensors can only measure the flight altitude relative to their starting position and not the actual altitude over current terrain or vegetation.

For features such as ‚return to home‘, with the aircraft automatically flying back to its starting position, automated landing and take-off, additional sensors are needed for altitude measurements. In these scenarios obstacle avoidance is an important task. For altitudes up to 5 m ultrasound sensors are mounted on the bottom of the aircraft [1]. In addition also monocular video sensors mounted on the bottom and in front of the aircraft are used. These sensors can also be used for indoor navigation, where no GPS signal can be received. The precision range for the combination of these two sensors is stated to 0.3 m to 13 m in downward and 0.7 m to 15 m in forward direction [2]. As monocular sensors are camera based sensors, they are strongly influenced by lighting conditions and contrast. In addition, also the surface texture influences the performance of these sensors.

With a radar-based altimeter these limitations can be overcome, as radar systems are robust against weather and lighting conditions. UAVs equipped with radar sensors are presented in [3] at 24 GHz with 250 MHz bandwidth and in [4] at 94 GHz with 1 GHz bandwidth, used for synthetic aperture radar (SAR) remote sensing.

Figure 1. Picture of the hexacopter with mounted radar altimeter.

In this paper, a 77 GHz radar sensor with 2 GHz bandwidth, capable of precise measurements of the actual altitude over current terrain and vegetation at altitudes higher than 15 m with a range-resolution of 7.5 cm is presented.

II. Experimental Setup

The base of the experimental setup is a hexacopter build from off-the-shelf components, capable of lifting 1.5 kg payload for around 15 minutes. The hexacopter is equipped with a DJI Naza flight controller, containing a build in IMU with accelerometer, gyroscope, and barometer, a GPS/compass module providing good flight stability and maneuverability. The flight controller also hands over the initialization, the start and the stop command from the remote controller to the controller of the measurement system. The measurement system is mounted on top of the hexacopter. A picture of the complete setup is depicted in Fig. 1, and a block diagram of the experimental setup is shown in Fig. 2.

A. Measurement System

The actual measurement system is electrically separated from the hexacopter and is powered with a second battery. A Raspberry Pi 2 single-board computer acts as the measurement controller and stores the measurement data with time stamps from a second IMU (MPU6000

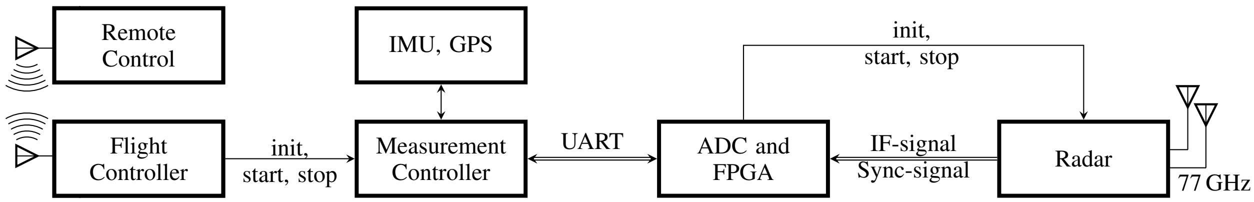

Figure 2. Experimental setup block diagram, depicting interconnections between functional blocks and data flow.

motion sensor and MS5611 barometer) and GPS (uBlox NEO-7M), as well as handling the communication with the ADC and FPGA board (Red Pitaya) via UART. The ADC and FPGA board triggers the radar sensor, samples the intermediate frequency (IF), and stores the results. The sample rate 1.9 Msps of the ADC is determined based on the required 15 measurements per second, the available file space, and a flight time of approximately 15 minutes.

B. Radar Sensor

A bistatic single channel frequency-modulated continuous wave (FMCW) radar with a center frequency of 76.5 GHz is used for the presented radar altimeter. The transmitted power is 5.5 dBm, and two standard gain horn antennas with 25 dBi gain are used for both the transmitter and the receiver, resulting in an effectively isotropically radiated power (EIRP) of around 1 W. Chirp-sequence frequency modulation is chosen because of the expected multi-target scenario [5], though velocity information is not of interest in this application. For high range resolution a bandwidth of 2 GHz (respectively 7.5 cm) is used. Due to the limited sampling frequency of 1.9 MHz the ramp duration is set to 1 ms and the ramp repetition interval results in 1.01 ms. For each measurement five ramps are transmitted.

To avoid aliasing a 5th order Butterworth low-pass filter with a 3 dB cut-off frequency of 820 kHz is used, limiting the maximum gaugeable height to 60 m.

The measured data is processed offline. At first, a Hann window is applied to the time domain data, second a fast Fourier transformation is performed and targets are extracted using a cell-averaging constant false alarm rate (CFAR) algorithm [6].

III. Measurement Results

In this section the proposed radar based altimeter is verified by multiple measurements and the influence of different terrain and large roll/pitch angles is considered. In addition, compared to traditionally used altimeters for UAVs (barometric, GPS sensors), the feasibility of detecting vegetation and complex terrain shapes is tested. The radar is calibrated to zero distance at the drone skids using a corner reflector in a distance of 1 m.

At first the signal to noise ratio (SNR) for different altitudes over grass is investigated. The range spectrum of the regarded altitude of up to 40 m is depicted in Fig. 3. The stationary false targets at 37 m (respectively 500 kHz), caused by a not properly filtered step-down converter is also visible. For an altitude of 10 m, a SNR of 33 dB is achieved. The SNR decreases with increasing altitude to 19 dB at 20 m and 10 dB at 34 m. Based on the SNR, the CFAR algorithm can reliably detect altitudes up to 40 m.

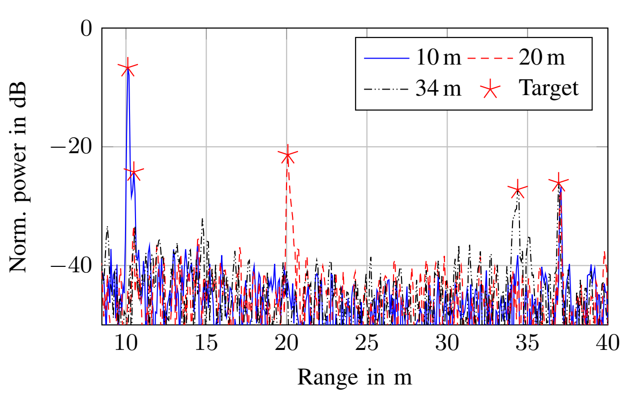

Figure 3. Range FFT for different altitudes over grass. Detected peaks are marked (✳).

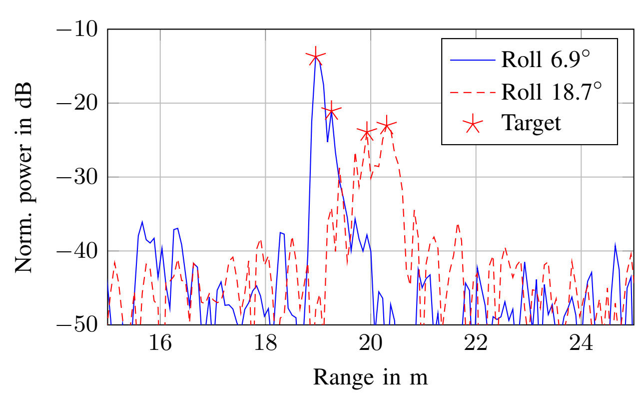

Figure 4. Influence of tilt (different roll-angle) due to acceleration of the drone on the SNR and peak width.

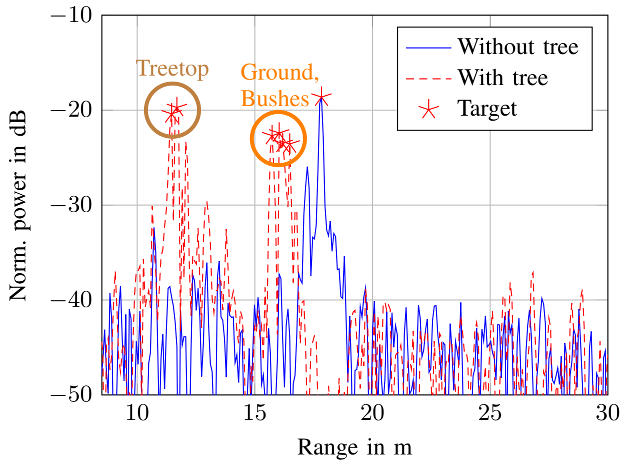

Figure 5. Detection of vegetation in addition to the actual altitude over ground, resulting in additional peaks and clutter.

When the drone accelerates, the drone tips and the pitch/roll angle increases. Because the used antennas are very focused (3 dB beamwidth of 7°) only a part of the reflected power is received leading to a decreased SNR and a wider peak compared to a nearly orthogonal position to ground. For an altitude of around 19 m over flat terrain with grass, Fig. 4 depicts these two cases. The SNR is decreased by 10 dB, but the CFAR algorithm still detects the ground as a target. As a result, even for large tilt the altimeter provides reliable altitude data without the need of an additional gimbal.

The measurements show that not only the actual altitude over ground but also the distance to vegetation such as trees can be measured. In Fig. 5 measurement results with and without trees are shown. Comparing the two results, in addition to the altitude over ground (approx. 17 m), an overflown tree is detected. This is indicated by additional targets (approx. 12 m) caused by the treetop and higher clutter in the range from 10 m to 14 m. Similar results are achieved when flying over crop and bushes.

In the following measurement, the range resolution performance is tested with the UAV flying over a stepped stone wall. The masonry is build up of large wackes with four steps (representing five targets), each between 20 cm and 25 cm high. Fig. 6 depicts the masonry and the measurement results, with the last target being a false target, caused by the power supply. Four of the five expected targets are identified by the CFAR algorithm. In Fig. 7 an excerpt of a flight starting on top of the stone masonry with the measured altitude of the barometric, the GPS and the radar sensor are depicted. The barometric and the radar sensor show very good correlation, whereas the GPS deviates a lot. At the marked areas (a) and (b) the horizontal passing of the previously described stone masonry is visible as clear steps in the radar data but not in the barometric data. Compared to the combination of ultrasonic and monocular sensor the radar sensor provides accurate data far beyond 15 m altitude.

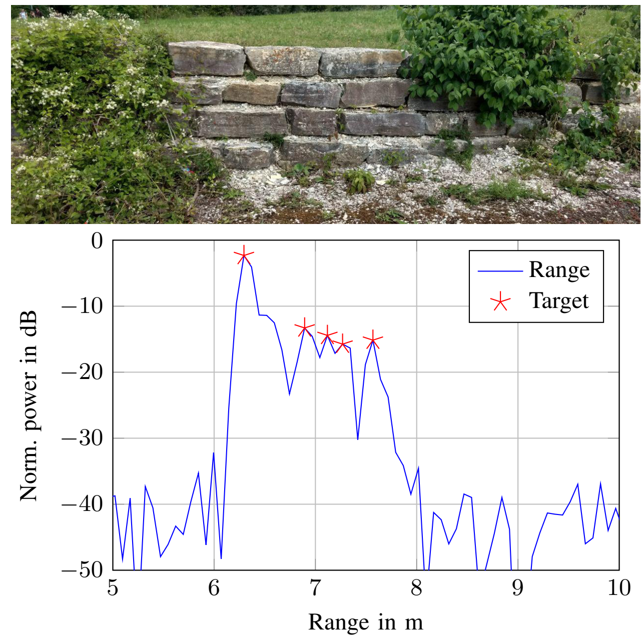

Figure 6. Stone wall and measured altitude with four of five detected steps as targets.

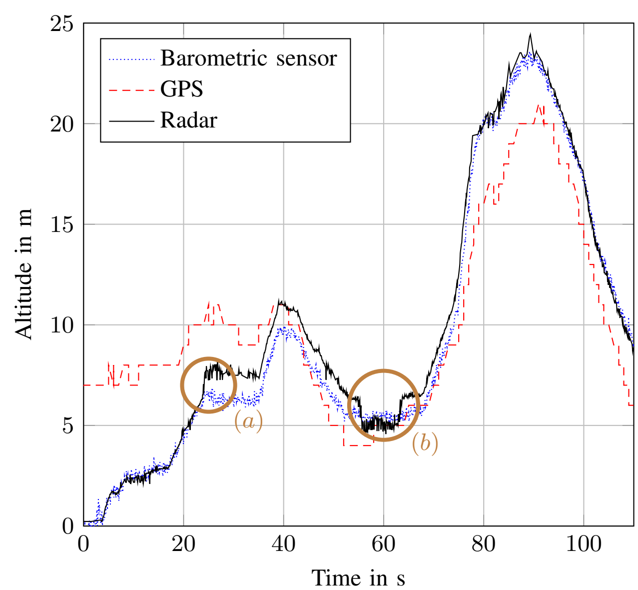

Figure 7. Comparison of measured altitude for barometric, GPS, and radar sensor. Overflown masonry visible in radar data, marked with circles (a) and (b).

IV. Conclusion

Altimeter measurements with a 77 GHz FMCW radar on a hexacopter have been performed. The maximum measured altitude over ground is 34 m. The possibility of detecting different vegetation (trees) and terrain (stone wall) has been shown. In addition the influence of tilt caused by movement of the drone has been examined.

Acknowledgment

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