122 GHz Monostatic Radar Altimeter for Automated UAV Landing

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Abstract—Landing maneuvers are critical tasks for unmanned aerial vehicles (UAVs) and need very precise information on the altitude above ground level (AGL). Radar is a suitable technology for this application, because it can not only sense the altitude AGL but also the rate of descent. In addition, obstacles or unsuitable terrain for landing can be detected. With the 122 GHz monostatic radar sensor presented in this paper, high bandwidth can be achieved in order to obtain range resolution in the single digit cm-range. Measurements are performed for different bandwidths to verify the concept.

I. INTRODUCTION

Unmanned aerial vehicles based on multirotor rotorcrafts are used in a growing number of different application fields. These can range from simple toys to aerial photography and filming, monitoring air quality and pollution [1], etc. Independent of the application, all UAVs have to take-off, being airborne and touch down, with the latter being the most critical. A variety of sensors make it possible to perform this maneuver almost autonomously (with some limitation). An internal measurement unit (IMU) consisting of a gyroscope and an accelerometer as well as global navigation satellite system (GNSS) is normally used to stabilize the aircraft. The altitude related to the sea level (altitude above mean sea level (MSL)) can also be extracted from the GNSS sensor, but with low accuracy, whereas barometric sensors can provide high accuracy. With the flight controller combining this sensor data, the UAV can hover, hold position, or can fly to predefined way points. Using these sensors, automated landing is possible with the limitation that it must be at the starting position, or under surveillance of the UAV pilot, to make sure that the area beneath the UAV is suitable. This is because of the sensors not being able to measure altitude AGL.

The problem of autonomous/automated landing is not new, and discussed in detail in [2]. In order to extract the altitude AGL, many different techniques are compared. Vision based sensors can be used for this task, for example stereo vision, monocular vision or optical flow sensors. Drawback of these sensors are the sensitivity to contrast, lightning conditions and surface texture. This problem is increased in the last few centimeters before touch down when grass is disturbed (fast changes of the surface texture) and dust and particles are swirling around because of the air turbulences caused by the rotors. This also limits the use of ultrasonic and infrared sensors. In [3] and [4] radar altimeters at 77 GHz for UAVs

Fig. 1. Picture of the measurement system.

with 1 GHz and 2 GHz bandwidth are investigated. It is shown that not only the altitude AGL but also different parts of vegetation and the surface of the terrain is detectable. A 26 GHz pulse correlation radar presented in [5] with a range resolution of 15 cm shows similar results.

For landing applications and hovering in close proximity to ground, the range resolution as well as the close range performance (≤ 15 cm) must be improved. This is achieved with the 122 GHz monostatic radar altimeter proposed in this work. With a bandwidth of up to 5 GHz targets as close as 5 cm to the antenna aperture can be detected. In addition also the Doppler is evaluated in order to have a plausibility check against the motion control or to land on moving platforms such as ships or piers. The high operating frequency and the monostatic realization also improves size and weight which are important factors for smaller UAVs.

II. MEASUREMENT SYSTEM

For all measurements a test carrier based on a DJI Matrice 600 Pro hexacopter is used. It features three redundant IMUs and GNSSs to provide a highly reliable platform [6]. A flight time of approximately 15 min with a payload of 6 kg can be achieved. The power supply of the UAV and the measurement system are decoupled. A measurement PC mounted to the UAV handles analog-to-digital conversion and data storage.

A. Monostatic Radar Sensor

The radar system is build around a monostatic 122 GHz radar chip which is described in [7]. It consists of four stacked PCBs: A power-board, intermediate frequency (IF)-board, phased locked loop (PLL)-board, and the radio frequency (RF)-board. A basic block diagram with the most important building blocks is depicted in Fig. 2.

On the RF-board the bare die of the radar chip is glued in a cavity of a multilayer printed circuit board (PCB) consisting of a top layer 127 μm RO3003 substrate, 254 μm RO5880 substrate and FR4 carrier for mechanical stability. The radar chip includes a voltage-controlled oscillator (VCO) and divider, power amplifier (PA), and a high-isolation coupler to decouple transmitter and receiver. The receiving path is realized with a low-noise amplifier (LNA) and down-converting in-phase and quadrature (IQ) mixer. The differential RF pads are wire bonded using double bonds to a differential microstrip line (DMSL) which feeds a DMSL-to-waveguide (WG) transition to which a 26dBi WR08 standard gain horn (SGH) is connected. Noise suppression for all analogue supply voltages is performed using π -section filters consisting of decoupling capacitors and ferrite beads.

B. Modulation and Signal Conditioning

Chirp-sequence frequency modulation is chosen as modulation scheme in order to evaluate range and velocity in multi target scenarios. For the ramp generation a fractional-N frequency synthesizer ADF4159 PLL from Analog Devices is used. The reference frequency is provided by a surface acoustic wave (SAW) oscillator at 80 MHz. The loop filter (LF) is designed as a third order low-pass filter with a cut-off frequency of 250 kHz. The modulation parameters used in this paper are summarized in Table I, including the resulting range resolution, velocity resolution, and the maximum unambiguous radial velocity.

For signal conditioning, the IF-board features a programmable gain of 10 dB to 60 dB in 0.5 dB steps. All parts are selected as dual-channel devices to provide best possible matching between the IQ channels. The first device is an operational amplifier (OpAmp) (ADA4937-2) working as an impedance transformer with 10 dB fixed gain which is AC-coupled to the down-converting mixer outputs. Subsequently, a programmable gain amplifier (PGA) (HMC960) with a gain-range from 0 dB to 40 dB in 0.5 dB steps is connected. This is followed by a programmable sixth order Butterworth low-pass filter with bandwidths between 3.5 MHz to 50 MHz

Fig. 2. Block diagram of the 122 GHz monostatic radar sensor.

(HMC900). The filter also features an optional 10 dB gain stage. The last part is used to make an balanced to unbalanced (BALUN) conversion (AD8034) to feed the single ended ADC inputs.

C. Radar Performance

At the center frequency of 123 GHz the output power at the WG connection is characterized to be -13 dBm. This corresponds to an equivalent isotropically radiated power (EIRP) of 13 dBm. The output phase noise is characterized to -62 dBc/Hz, -58 dBc/Hz, -85 dBc/Hz and -110 dBc/Hz at 10 kHz, 100 kHz, 1 MHz and 10 MHz offset, respectively. The measurement rate of the radar is set to 15 Hz.

III. MEASUREMENTS

For all measurements the bandwidth of the IF filter is programmed to 7 MHz and the sampling rate is set to 20 Msps. This limits the maximum detectable range to 29 m for 5 GHz bandwidth. A Hann window is applied to the time domain data. Range-Doppler processing is done using a 2D-FFT and targets are extracted with a linear ordered statistic constant false alarm rate (CFAR) algorithm.

As the reference plane the aperture of the horn antenna is used (range equal 0 m). The distance between the reference plane and the landing skid is 10 cm, corresponding to the measured altitude AGL by the radar sensor when the UAV is on ground. Based on the extracted targets of the CFAR algorithm, the altitude AGL h_{radar} is tracked and the corresponding radial velocity is also extracted. This data is compared to the altitude and vertical velocity derived from the UAVs telemetry data. The telemetry data for the altitude h_{tele} is fused from the previously mentioned onboard sensors and is read out with 50 Hz. It uses the International Civil Aviation Organization (ICAO) standard atmospheric model, returning the altitude MSL. To derive an altitude relative to the starting position h_{rel} of the UAV, the mean of the first 100 altitude MSL measurements is subtracted:

$$h_{\text{rel}} = h_{\text{tele}} - \left(\frac{1}{100} \sum_{i=1}^{100} h_{\text{tele},i} \right) \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}.$$

TABLE I

OVERVIEW OF USED MODULATION PARAMETERS BANDWIDTH BW , CHIRP DURATION T_c , RAMP REPETITION INTERVAL T_{RRI} , NUMBER OF EVALUATED RAMPS N , RANGE RESOLUTION Δr , VELOCITY RESOLUTION Δv , AND THE MAXIMUM UNAMBIGUOUS RADIAL VELOCITY v_m .

BW GHz	T_c μs	T_{RRI} μs	N	Δr mm	Δv $\frac{\text{cm}}{\text{s}}$	v_m $\frac{\text{m}}{\text{s}}$
1	20	140	256	150	7.53	4.3
2	40	140	256	75	7.53	4.3
5	100	140	256	30	7.53	4.3

(a) Tracked altitude AGL from radar data h_{radar} and altitude relative to starting position from telemetry data h_{rel} .

(b) Radial velocity from radar data v_{radar} , and vertical velocity from telemetry data v_{tele} .

(c) Detail (I): UAV takeoff for 5 GHz bandwidth.

(d) Detail (I): UAV takeoff for 2 GHz bandwidth.

(e) Detail (I): UAV takeoff for 1 GHz bandwidth.

Fig. 3. UAV flight: Comparison of radar data with 5 GHz bandwidth to telemetry data from UAV. (a) tracked altitude AGL from radar data to altitude relative to starting position from telemetry data, and (b) radial and vertical velocity are depicted. Radar snapshots for detail (I) separated by 200 ms are shown for (c) 5 GHz, (d) 2 GHz and (e) 1 GHz bandwidth. Detected targets are marked with (X).

The result of a four minute flight comparing the telemetry data to the radar data with 5 GHz RF bandwidth is depicted in Fig. 3. As can be seen, the overall trend for the altitude Fig. 3(a) as well as the velocity Fig. 3(b) are in good accordance. The uneven surface and obstacles such as rocks lead to the discrepancy between the altitude AGL and the altitude relative to the starting position. The velocity discrepancy is mainly present in the regions where the vertical velocity of the telemetry data is around $0 \frac{\text{m}}{\text{s}}$. When the UAV is moving with constant altitude, the roll as well as the pitch angle are non zero. This leads to a higher radial velocity measured by the radar.

Detail (I) in Fig. 3(a) and (b) highlights the UAV takeoff, which is depicted in detail as three radar snapshots separated by 200 ms in Fig. 3(c) for 5 GHz bandwidth. From left to

right, the expected distance of 10 cm for the UAV on ground can clearly be extracted. The initial velocity of the next radar measurement is nearly identical to the velocity of the telemetry data, $10.6 \frac{\text{cm}}{\text{s}}$ and $10.7 \frac{\text{cm}}{\text{s}}$ respectively. In the last snapshot, the ascend of the UAV can clearly be examined. The same scenario is considered for a bandwidth of 2 GHz and 1 GHz and the results are plotted in Fig. 3(d) and Fig. 3(e). Regarding the case when the UAV is still on ground, the range resolution for 1 GHz and 2 GHz is not enough to detect the altitude AGL and is therefore not depicted. This is due to the leakage signal being spread in too many range cells overlaying the actual targets. With the presence of movement the close range performance is improved in both cases, due to the leakage signal only corrupting stationary targets. The range resolution in the case of 1 GHz is not enough and leads

Fig. 4. Resulting range-velocity plot for hovering in close proximity to ground with high grass and a bandwidth of 5 GHz. On the camera image the waving grass causing Doppler frequencies can be seen. Detected targets are marked with (X).

to discrepancies of around 10 cm. For 2 GHz bandwidth the range resolution is fine enough to obtain reasonable results. With 5 GHz bandwidth the complete takeoff starting with the UAV being on ground and continuing the ascend of the UAV can be precisely captured.

Moving further along the time axis the maximum altitude of the flight is reached around 40 s. The altitude AGL is 15.2 m with a signal-to-noise ratio (SNR) greater 10 dB. Taking into account a common maximum vertical velocity for UAVs of around $\pm 5 \frac{\text{m}}{\text{s}}$ [6], a maximum range of at least 15 m for altitude AGL measurement and target detection is sufficient for takeoff and landing application.

Next, detail (II) in Fig. 3(a) is examined. The UAV is hovering in close proximity to ground with high grass. A camera image as well as the corresponding range-velocity measurement is shown in Fig. 4. Beside the altitude AGL at 40 cm, there are additional closer targets. As a result of the high carrier frequency of 122 GHz also small features of vegetation, e.g. high grass, can be detected. The targets, representing the grass, exhibit velocity parts because they are disturbed by air turbulences from the rotors. Comparing the altitude AGL from the radar measurement and altitude relative to the starting position reveals an offset of approximately 40 cm. This emphasizes the need of sensors like the presented radar altimeter which can sense the altitude AGL and in addition small scaled features of the surrounding. This necessity is emphasized in detail (III) in Fig. 3(a). The UAV is passing a steep slope twice and the offset between the radar and telemetry data amounts to 1 m.

The final touchdown of the UAV is highlighted in detail (IV), shown in Fig. 3(a). The landing place is not identical to the launch site, resulting in a negative altitude for the telemetry data. The corresponding radar measurements are depicted in Fig. 5. Similar to the takeoff, the radar altimeter can monitor the descending and final touchdown precisely.

Fig. 5. Range-velocity plots with 5 GHz bandwidth for the final touchdown of the UAV tagged as detail (IV) in Fig. 3(a) separated by 66.67 ms. Detected targets are marked with (X).

IV. CONCLUSION

For automated landing of UAVs and hovering in close proximity to ground, the precise altitude AGL must be known. On the basis of the discussed measurements it can be concluded, that the presented 122 GHz radar altimeter satisfies all requirements. Especially in the absence of movement the high bandwidth of 5 GHz is essential for the close range performance. In addition also small sized features of the surrounding such as high grass can be sensed.

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