Synthetic Aperture Radar Imaging Using a Small Consumer Drone

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Outline

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Motivation

- Small drones have become popular for aerial photography.
Motivation

• What happens when you mount a radar on the drone?
Motivation

- Small drones have become popular for aerial photography.
- Radar imaging could provide complementary information and extended operating conditions.
- Applications in scientific, agricultural, and environmental monitoring.
- UAV-SAR systems exist but are typically too heavy and need to be supported by large UAVs [1-3].

Objective

Develop and demonstrate a low-cost SAR system that is mounted on a small consumer drone (DJI Phantom 2).

Scientific Question: Can a low-cost, high-resolution SAR system be realized on a small consumer drone (whose maximum payload is typically less than 1 lb)?
PulsON 410 UWB Radar

- PulsON 410 (P410) radar by Time Domain Corporation.
- Board is 7.6 cm x 8 cm x 1.6 cm, weighs 58 grams, and can be battery powered.
- Emits short pulses at a pulse repetition frequency of 10 MHz.
- Equivalent frequency bandwidth from 3.1 to 5.3 GHz centered at 4.3 GHz.
- USB interface to control radar and transfer range profiles.
Drone SAR System

SAR system consists of P410 radar, Raspberry Pi + Wi-Fi Dongle, helix antennas mounted on aluminum ground planes. Entire system (including cables and batteries) weighs less than 300 g.
Drone SAR Prototype Photos

Helix Antennas

Raspberry Pi

Radar
Helix Antennas

- Broadband 5-turn helix antenna centered at 4 GHz.
- Supported by 3-D printed mold.
- Aluminum ground planes.
- 1 right-hand CP for Tx, 1 left-hand CP for Rx.
- Gain: $\sim 10$ dB; Two-way 3 dB beamwidth: $\sim 15^\circ$
Measurement Range Profiles

- Measured range profiles are real valued but finely sampled in time.
- Use FFT to get the complex frequency response and only keep data from 3.1-5.3 GHz.
Validation on Corner Reflectors

- 4 small aluminum trihedrals as point-scatterer targets.
- Range profiles collected (at 20 Hz) by flying drone in a straight line across measurement scene.
- Prominent persistent scatterers facilitate range alignment for image formation.
Motion Compensation

- Range profiles show significant range migration.
- Align to closest scatterer.
- Good agreement with point-scatterer simulation.
Image Formation

• Frequency/angle data are placed in $k$-space.

$$Image(r, cr) = \int \int E^s(f, \phi) e^{ik_xr} e^{ik_yr} dk_x dk_y$$

where

$$\begin{cases} 
    k_x = \frac{4\pi f}{c} \cos \phi \\
    k_y = \frac{4\pi f}{c} \sin \phi
\end{cases}$$

\[ \phi = \cos^{-1}\left(\frac{R_{\text{min}}}{R}\right) \]

• Polar reformat to uniform $k_x$-$k_y$ space and take 2-D inverse fast Fourier transform to obtain image.
• 3 focused scatterers. Cross-range smearing of farthest scatterer due to near-field effects.
• Good agreement between simulation and rail-SAR.
• More blurred result in drone-SAR.
Application to Other Targets

- Trihedral is left in the scene for reference.
- Stationary vehicle and human targets.
- Able to generate SAR images of other targets.
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Recap

• Devised a portable, lightweight SAR system that can be mounted on a small drone.
• Verified its imaging capability on trihedrals and then collected preliminary data of other targets.

• Current work.
  – Near-field correction
  – Downward-looking SAR
Near-Field Effect Correction

• Previous: used far-field FFT-based imaging scheme on near-field data.
• Solution: apply near-field backprojection imaging scheme.

Diagram:

- Near-Field Data
- Far-Field FFT-Based Imaging
- Near-Field Backprojection
- Final Image
Near-Field Backprojection

- Matched filter algorithm that projects the scattered field data into the phase function.

\[
SAR(r, cr) = \frac{1}{NM} \sum_{n=1}^{N} \sum_{m=1}^{M} E_s(x_n, f_m) \times e^{j\frac{4\pi f_m}{c} \sqrt{(cr-x_n)^2+(r+y_o)^2+z_o^2}}
\]
Near-field effects have been removed.
Good agreement between rail-SAR and simulation.
More blurred result in drone-SAR.
Point antennas at the ground in order to change imaging plane.
Preliminary Investigation

• Currently mounted on a vehicle for preliminary investigation.
• Attached drone-SAR system on extension pole and pointed downward.
• Drive across parking lot and collect range profiles.
• Strong ground bounce and minor residual platform returns.
• Height information is captured.
• Multiple scattering is visible.
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• Strong ground bounce and minor residual platform returns.
• Height information is captured.
• Multiple scattering is visible.
• Devised and demonstrated a portable, lightweight SAR system that can be mounted on a small drone.

• Pros:
  + Low-cost and portability opens up many new possibilities for in-situ measurements that were prohibitive in the past.

• Cons:
  – Needs prominent scatterer (absence of navigation data).
  – Drone flight instability.
Future Work

• Continue downward-looking SAR for frontal view imaging of targets.
• Examine radar signatures under co-polarized and cross-polarized scenarios.
• SAR imagery of targets through optical obstructions (smoke, foliage).
• Blind motion compensation / obtain navigation data.
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