Signal Processing Techniques for Imaging Radar

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Outline

• Why Imaging Radar

• Signal Processing for Imaging Radar
  – Typical Signal Processing Flow
  – Detection techniques
  – High angle resolution techniques

• SAR Imaging Radar
  – MIMO SAR Signal Processing
  – MIMO SAR Prototype System
Why Imaging Radar
Why Imaging Radar is a Game Changer in Automotive?

Radar is the only sensor that keeps performance over weather and visibility conditions.

High Azimuth Angle Resolution with MIMO

Two cars in adjacent lanes 100m range
Angle Resolution required - $\phi_{az} < 1.7^\circ$
Why Imaging Radar is a Game Changer in Automotive?

Today radar system is programmed to ignore high-mounted objects such as road signs and, possibly, the flanks of a semi truck, to avoid undesired braking events.

Overhead bridges/tunnels

High Elevation Angle Resolution with MIMO

Imaging Radar ~ 1° both Azimuth & Elevation
The Radar Sensor will become the primary sensor in the car

e.g. static truck stalled under a bridge
Angle Resolution required - $\phi_{el} < 1.4^\circ$
Imaging Radar for Industrial Applications

- 3-D holographic millimeter-wave (mmWave) imaging technology has a wide range of applications including security, medical, Robotics, etc.

- **Security Check**
  - At airport

- **Package Scanning**
  - See through package without open

- **Autonomous Delivery**
  - On the road delivery

- **Driverless Forklifts**
  - Loading/unloading pallets, lifting/transporting heavy loads
Signal Processing for Imaging Radar
Tradeoff for Various MIMO Schemes

- MIMO utilizes multiple orthogonal waveforms to achieve a larger virtual array than possible with the physical array.
- Multiplexing of the transmitters can be in frequency (FDM), time (TDM), code-space (CDMA) or a combination of the above.

<table>
<thead>
<tr>
<th>Schemes</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| TDM                         | - Perfect orthogonality  
- Low range/Doppler side-lobes | - Reduced instantaneous transmit power  
- Reduced max velocity unambiguity range |
| FDM                         | - Good orthogonality  
- Higher transmit power | - Smaller transmission bandwidth  
- Higher range/Doppler side-lobes  
- High ADC sampling rate |
| CDMA with Random Sequence   | - Higher transmit power  
- No penalty on max velocity | - Requires long sequence to have low cross-correlation, which increase frame size and thus computational cost  
- High Doppler side-lobes (in slow-time CDMA) or high Range side-lobes (in fast-time CDMA) |
| Coded MIMO with Fixed Sequence | - Good orthogonality  
- Higher transmit power | - Reduced max velocity unambiguity range, need algorithm to fix |

Typical Signal Processing Flow

- RF → AFE → range FFT → memory → Doppler FFT
- Pre-processing: DC correction, noise filter
- Coherent or non-coherent integration
- Detection, Angle finding, Tracking, Classification, SLAM

Pulse train for coherent processing:
- transmitted pulse train (frequency versus time)

Range FFT:
- slow time, fast time

Doppler FFT:
- slow time, range

Identified targets

Data collected over one frame

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Detection Techniques

- **CFAR (Constant False Alarm Rate) – CA (Cell Averaging)**
  - Optimum detection scheme in a homogenous background
  - Detection performance worsens when multiple targets appear in close range, the noise estimation unnecessarily increased by objects or clutter falling into noise reference zone

- **CFAR-OS (Order Statistics)**
  - Noise estimated using $k^{th}$ smallest sample in the reference window, so it can tolerate up to $(N-k)$ objects
  - However, this method requires higher computational cost due to sorting

- **Statistical tools, i.e. Histogram**
  - Use statistical information to decide detection threshold adaptively
Angular Resolution

- In the context of our FMCW radar, angular resolution defines the ability to separate two targets that fall within the **same range-Doppler bin**
- Angular Resolution depends on the antenna beam-width (limited by the antenna aperture $A_{eff}$)

Planar wave-fronts from a target at angle $0^\circ$ ‘see’ the full physical aperture hence the resolution is best at bore-sight

Planar wave-fronts from a target at angle $\theta^\circ$ ‘see’ a smaller effective physical aperture hence the resolution gets worse as the sources move away from bore-sight

\[ \theta_{BW}[radians] = \frac{\lambda}{A_{eff}} = \frac{\lambda}{Ndcos} \]

for large $N$, where $N$ is the number of receiver elements and $d$ is the spacing between the elements

**Super-Resolution angle estimation algorithms aim to achieve resolution higher than the antenna aperture-limited resolution**
# High Angular Resolution Estimation Methods

<table>
<thead>
<tr>
<th>Class</th>
<th>Algorithms</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>Barlett Beamforming</td>
<td>Pros: Robust, Low computational complexity as FFTs can be used for implementation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cons: Aperture-limited resolution; Resolution independent of the SNR</td>
</tr>
<tr>
<td>Adaptive</td>
<td>Capon (MVDR)</td>
<td>Pros: Resolution can potentially exceed the aperture-limited resolution provided the following conditions are met</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cons: SNR is moderately high; need sufficient number of snapshots</td>
</tr>
<tr>
<td>Sub-space Methods</td>
<td>MUSIC (Multiple Signal Classification)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ESPIRIT (Estimation of Signal Parameters via Rotational Invariance Techniques)</td>
<td></td>
</tr>
<tr>
<td>Parametric Methods</td>
<td>DML (deterministic maximum likelihood), SML (stochastic maximum likelihood)</td>
<td>Pros: Can work with Coherent Sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cons: Accurate Initialization required, Multidimensional search required</td>
</tr>
<tr>
<td>Non-Parametric Methods</td>
<td>IAA (Iterative Adaptive Approach)</td>
<td>Pros: Can work with Coherent Sources, single snapshot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cons: High computational cost</td>
</tr>
<tr>
<td>Compressive Sampling</td>
<td>$L_0 / L_1$ optimization: OMP, BPDN, YALL1, etc.</td>
<td>Pros: Can work on a “single shot”; can also work with correlated sources</td>
</tr>
<tr>
<td></td>
<td>$\min_{x} |x|_1 \text{ s.t. } Ax = y$</td>
<td>Cons: Off grid issue: If the actual signal is not on the grid over which the signals are searched then performance is not very good; high computational cost</td>
</tr>
</tbody>
</table>

**References:**
MUSIC (Separation of two static cars with 86 virtual channels)

Not enough angular resolution. The two cars merge into one another.

- Both the cars occupy the same Range-bin corresponding to the 112 meters distance.
- Angular spectrum from conventional FFT algorithm shows the two cars merged into a single peak.
- Angular spectrum obtained from MUSIC clearly shows the ability to resolve the two cars as separate targets.
## Computational Complexity (MUSIC)

<table>
<thead>
<tr>
<th>Steps (Per Range-Bin)</th>
<th>Computational Complexity</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covariance matrix (Estimated using L snapshots)</td>
<td>O(LM²)</td>
<td>14400</td>
</tr>
<tr>
<td>Eigenvalue decomposition</td>
<td>O(M³)</td>
<td>13824</td>
</tr>
<tr>
<td>MUSIC Spectrum (Evaluated at J sampling points)</td>
<td>J*(M-K)*M</td>
<td>46080</td>
</tr>
<tr>
<td><strong>Total Cycle Count (single Range-bin)</strong></td>
<td>LM² + M³ + J(M-K)M</td>
<td>74,304</td>
</tr>
</tbody>
</table>

### Implementation overhead
- 5

### Number of range bins
- 128

### Time (ms) @1GHz clock, 1 multiplication per clock
- 47.6

**Uniform Linear Array**

- N : Number of virtual Channels
- M : Number of channels in the sub-array
- J : Number of scanned angles
- K : Signal sub-space dimension
- L : Number of Snapshots

\[ P_{\text{MUSIC}}(\theta) = \frac{1}{a(\theta)^H E_N E_N^H a(\theta)} = \frac{1}{\| E_N^H a(\theta) \|^2} \]

where \( \theta \in \left[ -\frac{\pi}{2}, \frac{\pi}{2} \right] \), \( E_N \in \mathbb{C}^{(M)(M-K)} \)
# Sparse Linear Array Design

- Increase aperture size with sparsity to improve angle resolution

<table>
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<tr>
<th>Sparse array design</th>
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<th>Performance</th>
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</table>
| MRA                 | Minimum redundancy array (by Alan 1968) | ▪ No grating lobe but high side lobe to be suppressed  
▪ Known array for size < 11, no analytical form  
▪ Need signal decorrelation |
| Nested array        | Inner array and outer array have different space gap (by Piva 2010) | ▪ Obtain $O(N^2)$ DOF using $N$ physical sensors, improved sparsity than MRA  
▪ Have closed analytical form  
▪ Need signal decorrelation |
| Global optimization | Minimize sidelobe, i.e. particle swarm optimization | ▪ No analytical solution  
▪ Pick sparse array to minimize peak sidelobe level  
▪ Work overhead for antenna array design |

<table>
<thead>
<tr>
<th>Sparse array processing</th>
<th>Class</th>
<th>Algorithms</th>
<th>Performance</th>
</tr>
</thead>
</table>
| Array interpolation / extrapolation | Fill up holes in a sparse array with interpolation (linear, IIR) | ▪ Works for small number of holes  
▪ Performance depends on SNR  
▪ Computational efficient |
| Matrix completion | Use matrix completion (SVT) technique to fill up the sparse array (low rank Hankel matrix) | ▪ Allows larger number of holes  
▪ Subarray design need to meet low rank condition  
▪ Relatively higher computational cost |

References:
SAR Imaging Radar
SAR Imaging Radar Challenges

Challenges:

- Achieve high-resolution with as few antenna elements as possible
- Multiple-input multiple-output (MIMO) radars increase the degrees of freedom
- The complexity of extremely dense transceiver electronics limits the use of MIMO only solutions
- Hybrid concepts combining synthetic aperture radar (SAR) techniques and MIMO arrays:
  - Present a good compromise to achieve short data acquisition time and low-complexity.
MIMO-SAR IMAGE RECONSTRUCTION PROCESS

• High level signal processing chain for image reconstruction:
  – Near field calibration: Estimate the position of the reference target; estimate calibration parameters based on reference target
  – Convert to Monostatic: compensate phase of each MIMO channel
  – Image reconstruction: FFT based reconstruction

References:
Example MIMO SAR System

- A faster and bigger scanner has been designed, multi-chip cascaded sensors has been integrated

- Scanning area:
  - 1000 mm by 1000 mm
- Maximum speed:
  - 400 mm/s at both axes
MIMO SAR Image Results

See through box

See through clothe
Thanks You