Advancement of AI and Simulation Intersecting mmWave Radar

Chulong Chen¹, Jingyi Ma¹, Pradyumna Singh¹, Xiaodong Cai², Margaret Huang¹

¹Intel Labs, ²Intel IPSG
Agenda

- Application domains of mmWave sensing
- Introduce today’s challenge
- Bio-Inspired mmWave sensing and perception
- Pyramid of mmWave perception simulation environment
- Case studies
- Conclusion & Q&A
Application domains of mmWave sensing

- Less privacy sensitivity
- Robustness to weather and lighting conditions
- New sensing dimensions and modality

<table>
<thead>
<tr>
<th>Privacy Sensitive</th>
<th>All weather &amp; lighting</th>
<th>Modality/Redundancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elderly Care</td>
<td>🤖 Intrusion Detection</td>
<td>🖥️ Human-machine Interface</td>
</tr>
<tr>
<td>Patient Monitoring</td>
<td>🏠 Industrial/Mining</td>
<td>🛡️ Automotive</td>
</tr>
<tr>
<td></td>
<td>Monitoring</td>
<td></td>
</tr>
<tr>
<td>Home Monitoring</td>
<td>🏡 Automotive</td>
<td>🤖 Robotics</td>
</tr>
</tbody>
</table>
Challenge

- Application specific design of hardware and software

- Artificial Neural Network (ANN) provides a promising solution

- How to efficiently generate dataset and train?
Case 1: Efficient CNN + FMCW Radar for Gesture Recognition [2] (I)

- Radar is near-perfect sensor for gesture recognition

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Field of View</th>
<th>Range resolution</th>
<th>Information captured</th>
<th>Anonymity</th>
<th>Bad weather</th>
<th>Price</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>radar</td>
<td>90°</td>
<td>2mm</td>
<td>Distance, velocity, angle</td>
<td>Yes</td>
<td>Good in fog, dust, smoke</td>
<td>$5</td>
<td>Medium</td>
</tr>
<tr>
<td>IR TOF Camera</td>
<td>60°</td>
<td>2cm</td>
<td>Texture, RGB, IR</td>
<td>No</td>
<td>Sensitive to light</td>
<td>$5</td>
<td>High</td>
</tr>
<tr>
<td>PIR</td>
<td>100°</td>
<td>N/A</td>
<td>Human in motion</td>
<td>Yes</td>
<td>Sensitive to light, heat</td>
<td>$1</td>
<td>Low</td>
</tr>
<tr>
<td>ultrasonic</td>
<td>100°</td>
<td>3mm</td>
<td>distance</td>
<td>Yes</td>
<td>Bad in smoke, dust</td>
<td>$1</td>
<td>Low</td>
</tr>
</tbody>
</table>

Case 1: Efficient CNN + FMCW Radar for Gesture Recognition (II)

- Three-channel input frames
  - Range-time trajectory
  - Speed-time trajectory
  - Azimuth-time trajectory
- Efficient DNN architecture
  - VGG-10
  - VGG-10 with Residual layers
Case 1: Efficient CNN + FMCW Radar for Gesture Recognition (III)

• FMCW radar with speed-spatial-angular resolution

• VGG-10+Resnet DNN architecture

• 96% real-time accuracy

Table 3: Accuracy comparison among models

<table>
<thead>
<tr>
<th>Network Architecture</th>
<th>Avg. Acc.</th>
<th>LEFT</th>
<th>RIGHT</th>
<th>CLICK</th>
<th>WRIST</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGG-10</td>
<td>91.0%</td>
<td>94.9%</td>
<td>80.7%</td>
<td>95.5%</td>
<td>97.0%</td>
</tr>
<tr>
<td>ResNet-20</td>
<td>98.7%</td>
<td>99.1%</td>
<td>99.0%</td>
<td>97.9%</td>
<td>98.9%</td>
</tr>
<tr>
<td>CNN+LSTM</td>
<td>78.0%</td>
<td>69.0%</td>
<td>49.5%</td>
<td>84.6%</td>
<td>90.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gesture ground truth</th>
<th>gesture prediction</th>
<th>none</th>
<th>left</th>
<th>right</th>
<th>click</th>
<th>wrist</th>
<th>prec</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>2189</td>
<td>18</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>98.5%</td>
<td></td>
</tr>
<tr>
<td>left</td>
<td>9</td>
<td>2118</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>99.1%</td>
<td></td>
</tr>
<tr>
<td>right</td>
<td>1</td>
<td>19</td>
<td>2055</td>
<td>0</td>
<td>0</td>
<td>99.0%</td>
<td></td>
</tr>
<tr>
<td>click</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>2150</td>
<td>40</td>
<td>97.9%</td>
<td></td>
</tr>
<tr>
<td>wrist</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>2215</td>
<td>98.9%</td>
<td></td>
</tr>
</tbody>
</table>

Question: Could the nature does it better?
Bio-Inspired mmWave sensing and perception

Coherent ranging and perception

- High range resolution (10ns) and angular accuracy (up to 0.7°)
  - Doppler shifts/modulation analysis
  - Target detection, object recognition, collision avoidance
  - Adaptation and cognitive behavior

ANN driven architecture

- Co-optimization of waveform and radio front-end design
- Deep Reinforcement Learning based waveform, modulation adaptation
- Coherent ANN optimized for I/Q input
- Costly to find training environment

Biologically inspired mmWave sensing and perception framework

- Evolution
  - FM Call
  - CF-FM
  - Clicks

- Cognition/Adapt
  - Search Mode
  - Approach Mode
  - Attack Mode

References:
Pyramid of mmWave perception simulation environment

- Multi-physics simulation
  - Physics engine
  - Ray-tracing based EM simulation
- Build application dataset with
  - mmWave digital assets
  - Radar sensor model
  - Scenario definition
- Train DNN with synthetic dataset
Case 2: Feasibility for simulation based Radar Dataset generation: Multi-path

- Multipath mitigation
- Turn enemies into friends – NLOS detection
- DL approach paired with simulation:
  - High complexity with conventional model-based approach
  - Can turn off multipath in simulation
  - Easy access to ground truth
Case 3: DNN for Object Class Estimation

- Synthetic dataset generated with multi physics simulation

<table>
<thead>
<tr>
<th>Car</th>
<th>Motorcycle</th>
<th>Person</th>
<th>Bike</th>
<th>Shopping cart</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Car" /></td>
<td><img src="image2.png" alt="Motorcycle" /></td>
<td><img src="image3.png" alt="Person" /></td>
<td><img src="image4.png" alt="Bike" /></td>
<td><img src="image5.png" alt="Shopping cart" /></td>
<td><img src="image6.png" alt="Truck" /></td>
</tr>
</tbody>
</table>

- Optimized DNN learned from MF-FFT processed 3D voxel dataset
  - > 99% classification accuracy,
  - < 7 deg orientation RMSE
Conclusion and Open Challenges

- Bootstrap R&D on mmWave sensing pipeline with simulation
  - Synthetic data generation
  - Readily available ground truth
  - Hand-craft/expand corner cases
  - Verification/validation

- Open Challenges:
  - Transfer trained models to field deployment
  - Find detailed simulation with highly dynamic scenarios
  - EM simulation in mmWave still need acceleration
Disclaimer

No license (express or implied, by estoppel or otherwise) to any intellectual property rights is granted by this document.

This document contains information on products, services and/or processes in development. All information provided here is subject to change without notice.

Contact your Intel representative to obtain the latest forecast, schedule, specifications and roadmaps.

The products and services described may contain defects or errors known as errata which may cause deviations from published specifications. Current characterized errata are available on request. No product or component can be absolutely secure.

You may not use or facilitate the use of this document in connection with any infringement or other legal analysis concerning Intel products described herein. You agree to grant Intel a non-exclusive, royalty-free license to any patent claim thereafter drafted which includes subject matter disclosed herein.

Forecasts: Any forecasts of requirements for goods and services are provided for discussion purposes only. Intel will have no liability to make any purchase pursuant to forecasts. Any cost or expense you incur to respond to requests for information or in reliance on any forecast will be at your own risk and expense.

Business Forecast: Statements in this document that refer to Intel’s plans and expectations for the quarter, the year, and the future, are forward-looking statements that involve a number of risks and uncertainties. A detailed discussion of the factors that could affect Intel’s results and plans is included in Intel's SEC filings, including the annual report on Form 10-K.

Copies of documents which have an order number and are referenced in this document may be obtained by calling 1-800-548-4725 or by visiting www.intel.com/design/literature.htm.

Intel, the Intel logo, [List the Intel trademarks in your document] are trademarks of Intel Corporation or its subsidiaries in the U.S. and/or other countries.

*Other names and brands may be claimed as the property of others

© Intel Corporation.
Thank you!