Connected Automated Driving
Overview, design, and technical challenges

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Automated Driving

Sensors are at the heart of Automated Driving Technology
## Challenges in Automated Driving Design

<table>
<thead>
<tr>
<th></th>
<th>ACCURACY/ RANGE</th>
<th>WEATHER</th>
<th>COST</th>
<th>URBAN/ NLOS SCENARIO</th>
<th>MAIN CHALLENGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAPPING</strong></td>
<td>Δ</td>
<td>O</td>
<td>Δ</td>
<td>O</td>
<td>Might not exist for all US roadways. Errors will exist.</td>
</tr>
<tr>
<td><strong>LOCALIZATION</strong></td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>GPS (including future GPS3) has challenges in lane level localization for urban canyon.</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>X</td>
<td>Δ</td>
<td>O</td>
<td>LiDar based localization can be costly and does not work well in bad weather.</td>
</tr>
<tr>
<td><strong>PERCEPTION</strong></td>
<td>Δ</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td>Limited range (around 50-80 m). Major challenges in NLOS and bad weather</td>
</tr>
<tr>
<td><strong>PATH PLANNING</strong></td>
<td>Δ</td>
<td>X</td>
<td>O</td>
<td>Δ</td>
<td>Challenges in Merging, NLOS Urban driving, Platooning</td>
</tr>
</tbody>
</table>

**LEGEND**
- **O** – good performance
- **Δ** – room for improvement
- **X** – challenges
What if we add Connected Intelligence to Automated Vehicles?

Connected Intelligence will help provide long range sensing, NLOS operations in a cost-effective manner with robustness for any weather condition.
What has been done so far on Connected Vehicles?

DSRC: Dedicated Short-Range Communication

Ad hoc networking technology that allows vehicles to communicate with each other, roadside devices, pedestrians, bicycles, trains, ...

CURRENT STATUS:
- Moving toward deployment
- Many stakeholders in US, China, Japan, Europe and elsewhere
Cooperative Automated Driving with highly improved mapping & localization, perception, and path planning
Cooperative Mapping Overview

Main Idea behind Cooperative Mapping:
Building real-time Automated Driving maps using the long-range of V2X

Significant improvement in road estimation as compared to using only local sensor data (Radar + Camera)
Detecting state of the Remote Vehicle (keeping its lane or changing lanes) is crucial for Cooperative Mapping.

When the vehicle is not changing lanes, its trajectory is a good indicator of lane geometry. In this scenario, V2V data from the remote vehicle can be used to augment accuracy of lane geometry estimation.

High detection accuracy achieved using Machine Learning Classifiers.
Cooperative Localization Overview

Main Idea behind Cooperative Localization:
Improving positioning by leveraging GPS receivers of neighboring vehicles

Flow of data between host vehicle and neighbors

Sensor Fusion block

Measuring error in Vehicle Positioning

43.8% Error Reduction
Cooperative Perception Overview

Main Idea behind Cooperative Perception:
Enhancing sensing range by sharing data (incl. camera, LIDAR, radar, etc.) with neighboring vehicles.
Cooperative Perception: Dynamic Object Detection

**PROBLEM:** Neural networks are unable to recognize all objects in certain conditions

**APPROACH:** Combine multiple perspectives from neighboring cars of the same scenario

Designed novel 3D Vision Fusion Algorithm to allow bounding boxes to be updated with greater precision and occluded/distant objects to be shared between vehicles.
Corolla Camera
neural network detects skateboarder

Prius Camera
neural network does not detect skateboarder

Other pedestrians detected
Skateboarder detected
Skateboarder not detected
CONFIDENCE LEVEL IN DETECTION

Corolla Detection

- Skateboarder
- Other pedestrians

Detected by Corolla

Prius Detection

- Skateboarder
- Other pedestrians

No detection by Prius

Original
- Mean
- Product
- $b=0.00$
- $b=0.25$
- $b=0.50$
- $b=0.75$
- $b=1.00$
- Fused

High confidence in FUSED VIEW
Cooperative Path Planning Overview

Main Idea behind Cooperative Path Planning:
Highway merging using V2X handshakes

Exchange V2V messages before merge to determine the merge order between on-ramp and highway vehicles

Reducing the wait time on-ramp before merge

25% Improvement in wait-time
Cooperative End-to-end Driving Overview

Main Idea behind Cooperative End-to-end Driving:
Achieve near 100% accuracy your vehicle’s end-to-end driving by utilizing data from neighboring connected vehicles.

What is End-to-end Driving?
Deep Learning to predict steering angles, required force on brake and gas pedals using sensor data.
Baseline scenario: Ego vehicle predicts steering angle using forward facing camera data

Input to neural network: Video frames

10 layer Video Neural Network

Steering Angle output of video neural network

Ego vehicle predicts steering angle using forward facing camera data.
Cooperative End-to-end Driving: V2V-based neural network - An alternative?

This is what the Ego vehicle measures independently:
- Latitude: $Lat_0$
- Longitude: $Lon_0$
- Heading: $\phi_0$

This is what the leading vehicle broadcasts:
- Latitude: $Lat_1$
- Longitude: $Lon_1$
- Heading: $\phi_1$

V2V Neural Network predicts the steering angle for Ego vehicle

$$x = \begin{bmatrix}
\text{Latitude difference} \\
\text{Longitude difference} \\
\text{Sine of heading difference}
\end{bmatrix} = \begin{bmatrix}
Lat_1 - Lat_0 \\
Lon_1 - Lon_0 \\
\sin(\phi_1) - \sin(\phi_0)
\end{bmatrix}$$

$2$ layer V2V Neural Network

Steering Angle output of V2V neural network
Cooperative End-to-end Driving: Combining video-based and V2V-based networks

Video-based prediction

\[ C_1^{\text{vid}} + C_2^{\text{V2V}} = F \]

Weighing network

V2V-based prediction

Final prediction

Weights
Good steering angle prediction using a neural network trained on integrated video and V2V data
New Communication Requirements..

<table>
<thead>
<tr>
<th>Application</th>
<th>Data</th>
<th>Rate</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperative Perception</td>
<td>Processed – detected objects</td>
<td>0.5  Mbps</td>
<td>60 byte/object, 100 objects, 10 Hz</td>
</tr>
<tr>
<td>Cooperative Perception</td>
<td>H.265/HEVC HD Camera - Raw</td>
<td>10  Mbps</td>
<td>640x360 resolution, compressed</td>
</tr>
<tr>
<td>Cooperative Perception</td>
<td>LIDAR - Raw</td>
<td>35  Mbps</td>
<td>6 vertical angels, 64 elements, 10 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>horizontal rotation</td>
</tr>
<tr>
<td>Cooperative Path Planning</td>
<td>Coarse driving intention</td>
<td>0.05 Mbps</td>
<td>Few 100 bytes (e.g. 500 bytes) / msg, 10 Hz</td>
</tr>
<tr>
<td>Cooperative Path Planning</td>
<td>Planned Trajectory</td>
<td>2.5  Mbps</td>
<td>32 byte / coordination, 10 msec resolution, 10 sec trajectory, 10 Hz</td>
</tr>
</tbody>
</table>

Total data rate per link: 50 Mbps.

For multiple links:

Requirement #1:

**Total system data rate target 10 Gbps**

(Link data rate @50 Mbps x Target to support 200 links)

Requirement #2:

**Latency target1 = 20 msec**

Ultra-low latency to support applications such as platooning

**Latency target2 = 100 msec**

For applications such as long range sensing, driving intention latency requirements would be relaxed (100 msec target)
Huge spectrum available at mmWave bands

Advancement in CMOS technology enables low cost mmWave devices**

60 GHz WiFi (WirelessHD, IEEE 802.11ad) is already on the market

* United States radio spectrum frequency allocation chart as of 2011
## Potential applications of mmWave Communications

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Category</th>
<th>Throughput</th>
<th>Latency</th>
<th>Network type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperative Perception</td>
<td>Traffic safety, efficiency</td>
<td>High</td>
<td>Low</td>
<td>V2V</td>
</tr>
<tr>
<td>Cooperative maneuvering</td>
<td>Traffic safety, efficiency</td>
<td>Moderate</td>
<td>Ultra-low</td>
<td>V2V</td>
</tr>
<tr>
<td>Map download</td>
<td>Traffic safety, efficiency</td>
<td>High</td>
<td>High</td>
<td>V2I</td>
</tr>
<tr>
<td>Live Perceptual data broadcast</td>
<td>Traffic safety, efficiency</td>
<td>High</td>
<td>Low</td>
<td>V2I</td>
</tr>
<tr>
<td>Sensor data gathering</td>
<td>Traffic safety, efficiency</td>
<td>Moderate</td>
<td>Moderate</td>
<td>V2I</td>
</tr>
<tr>
<td>Sending data for cloud processing</td>
<td>Can be any</td>
<td>Varied</td>
<td>Varied</td>
<td>V2I</td>
</tr>
<tr>
<td>Media download</td>
<td>Infotainment</td>
<td>Varied</td>
<td>High</td>
<td>V2I</td>
</tr>
<tr>
<td>Video steaming</td>
<td>Infotainment</td>
<td>High</td>
<td>Low</td>
<td>V2I</td>
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</table>
Key Takeaways

Cooperative Automated Driving can address gaps in current solutions:

**Mapping:** To estimate the geometry of roads in real-time by using sensor data from the vehicles ahead

**Localization:** To improve positioning by leveraging neighboring GPS receivers

**Perception:** To get multiple perspectives of same driving scene & significantly enhance dynamic object detection

**Path Planning:** To reduce on-ramp time using V2X-assisted highway merging

**End-to-end Driving:** To significantly improve performance by integrating video and V2V networks
Questions?

Thank You

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