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Selected Problems of High-Resolution Automotive Imaging Radar

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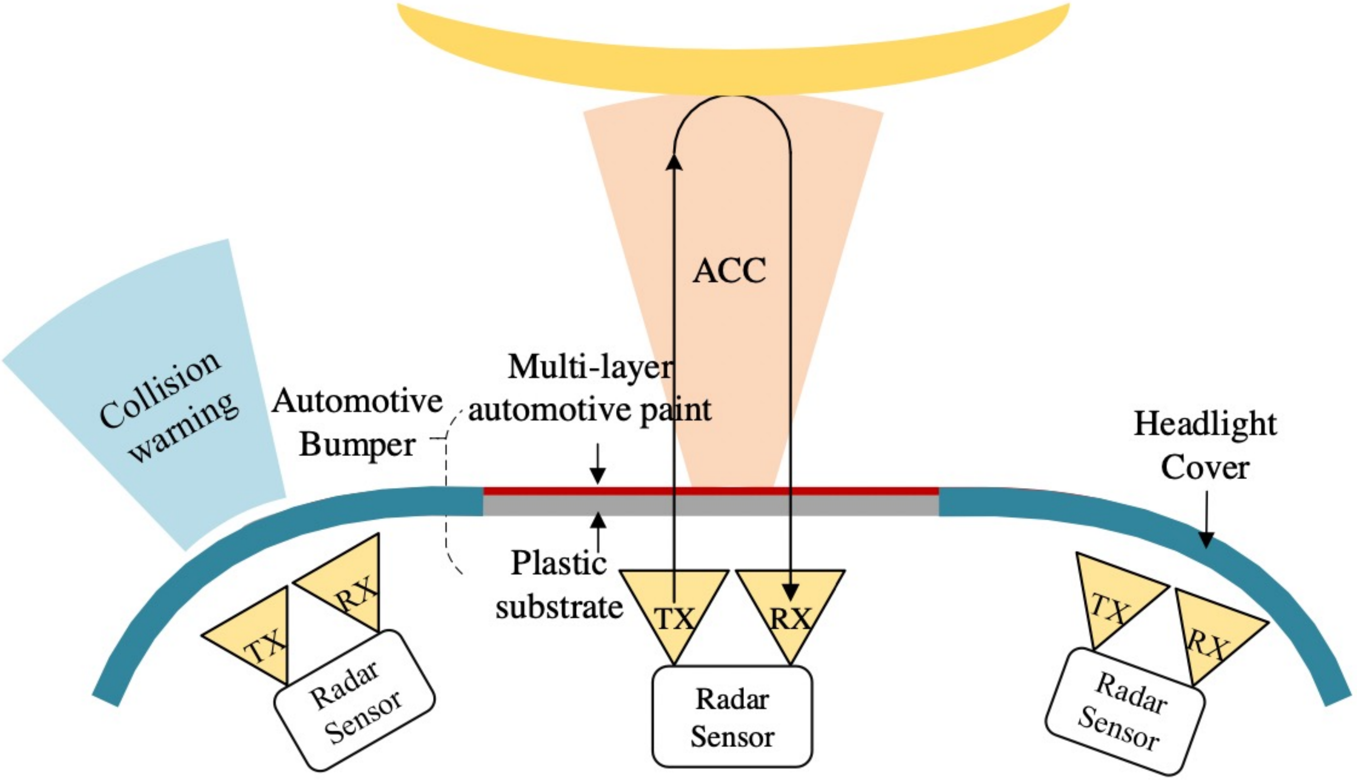
Motivation of Study on Transmissivity and Reflectivity o through Vehicle Infrastructure



Layout of potential automotive radar installation

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Two chapters included in this part of work:

- **Modeling and Experiment Verification of Transmissivity of Low-THz Radar Signal Through Vehicle Infrastructure**
- **Automotive Paint Permittivity Estimation in Low-THz frequency**

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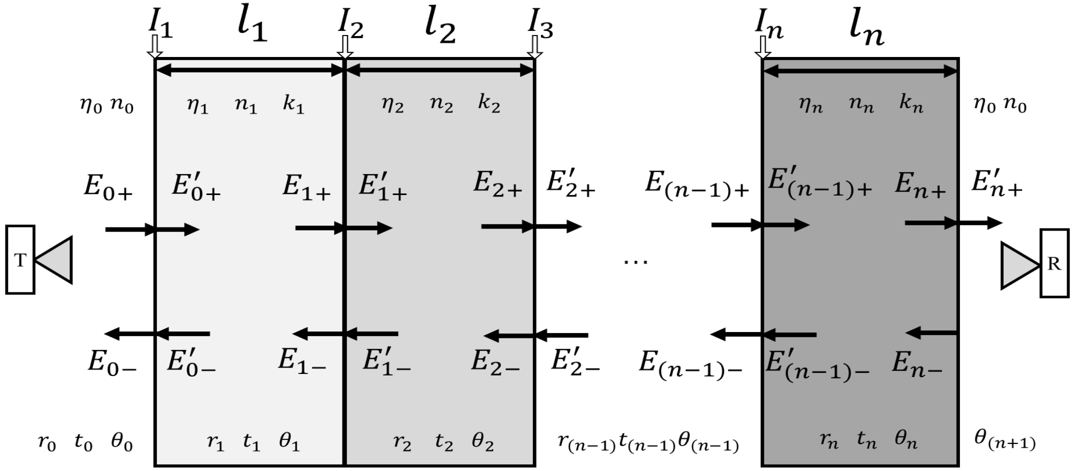
Electric field of transmission process:



Reflection coefficient

$$r_i = \frac{\eta_{i+1}cos\theta_i - \eta_i cos\theta_{i+1}}{\eta_{i+1}cos\theta_i + \eta_i cos\theta_{i+1}}$$

Transmission coefficient

$$t_i = \frac{2\eta_{i+1}cos\theta_i}{\eta_{i+1}cos\theta_i + \eta_i cos\theta_{i+1}}$$

Wave impedance: $\eta_i = \sqrt{\frac{j\omega\mu_i}{\delta_i + j\omega\varepsilon_0\varepsilon_i}}$

Wave number: $k_i = \omega\sqrt{\varepsilon_0\varepsilon_i\mu_i}$

Propagation matrix:

$$\begin{bmatrix} E_{0+} \\ E_{0-} \end{bmatrix} = \frac{1}{t_0}\begin{bmatrix} 1 & r_0 \\ r_0 & 1 \end{bmatrix}\begin{bmatrix} e^{jkl_1} & 0 \\ 0 & e^{-jkl_1} \end{bmatrix} \cdots \frac{1}{t_n}\begin{bmatrix} 1 & r_n \\ r_n & 1 \end{bmatrix}\begin{bmatrix} e^{jkl_n} & 0 \\ 0 & e^{-jkl_n} \end{bmatrix}\begin{bmatrix} E'_{n+} \\ 0 \end{bmatrix} = \begin{bmatrix} M_1 & M_3 \\ M_2 & M_4 \end{bmatrix}\begin{bmatrix} E'_{n+} \\ 0 \end{bmatrix}$$

Transmissivity: $T = \left|\frac{E'_{n+}}{E_{0+}}\right|^2 = \left|\frac{1}{M_1}\right|^2$

Reflectivity: $R = \left|\frac{E_{0-}}{E_{0+}}\right|^2 = \left|\frac{M_2}{M_1}\right|^2$

Definitions of parameters:

Parameters	Definitions
E_{i+}, E_{i+}, E'_{i+}	Incident, reflected and transmitted electric field
n_i	Refractive index of medium *i*
l_i	Thickness of medium *i*
ω	Angular frequency
μ_i	Permeability
δ_i	Conductivity
ε_0	Vacuum permittivity
ε_i	Relative permittivity of the material
θ_i	Incident ray angle

Experiment Verification of Transmissivity Through Vehicle Infrastructure and Permittivity of Automotive Paints

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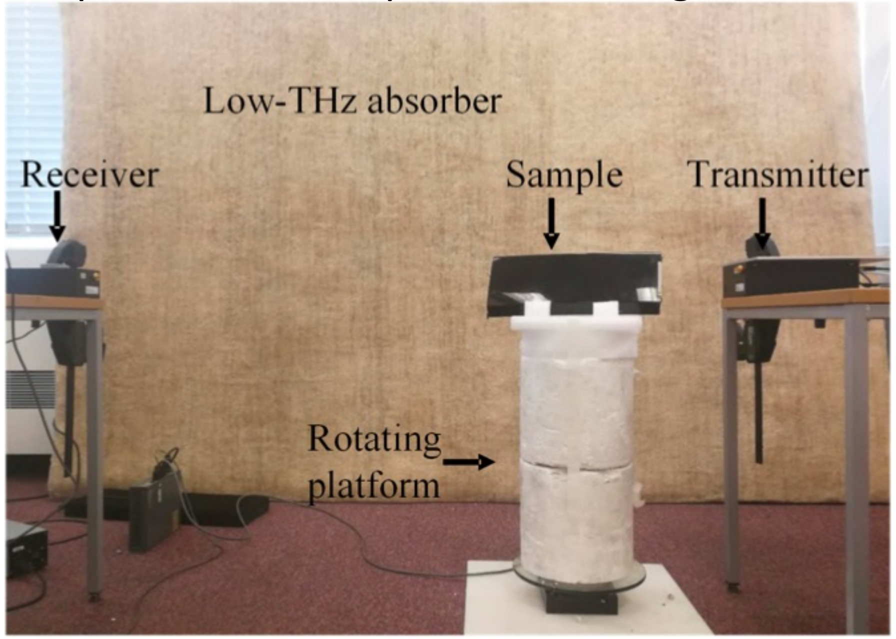
The experimental setup for measuring transmissivity

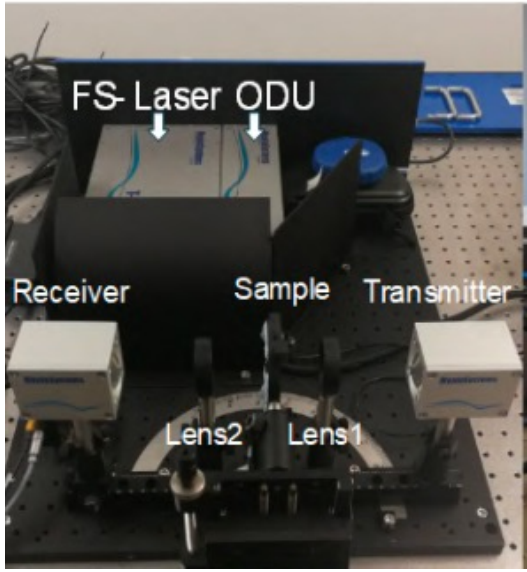


Parameters for 77 GHz, 300 GHz and 670 GHz radar systems

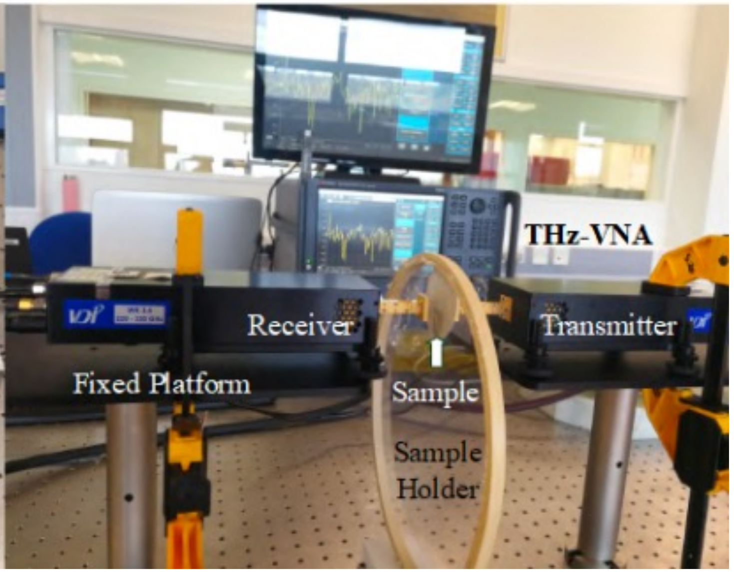
Frequency		77 GHz	300 GHz	670 GHz
Radar classification		FMCW	SFR	SFR
Frequency Bandwidth		76-81 GHz	282-298 GHz	656-672 GHz
PNA output power P_p		x	-15 dBm	-15 dBm
Transmitted power P_t		15 dBm	3 dBm	-10 dBm
Antenna Gain		20 dB	20 dB	24 dB
Azimuth/Elevation Beam width (-3 dB)		10°	10°	10°
F_p	CW experiment	x	7 GHz	7 GHz
	Bandwidth experiment	x	2-18 GHz	4-13 GHz
F_t	CW experiment	77-77.1 GHz	289 GHz	659 GHz
	Bandwidth experiment	76-81 GHz	282-298 GHz	656-665 GHz

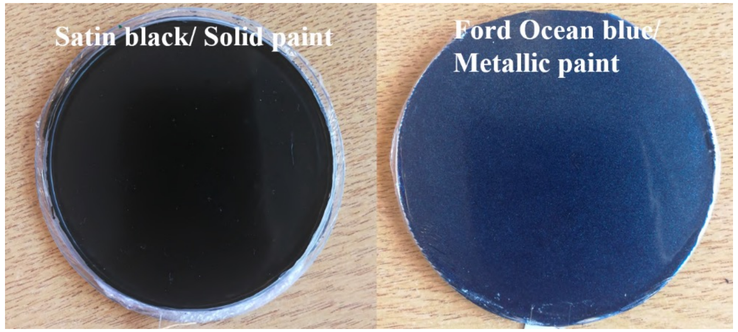
The experimental setup for measuring complex permittivity of automotive paints

THz-TDS



THz-VNA





Examples of paint samples

Frequency bands:

- TDS: 0.3-1THz
- VNA: 0.14-1.1THz

Measurement results of Transmissivity Through Vehicle Infrastructure and Permittivity of Automotive Paints

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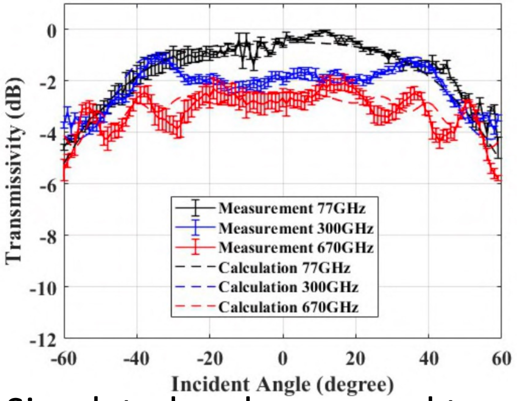
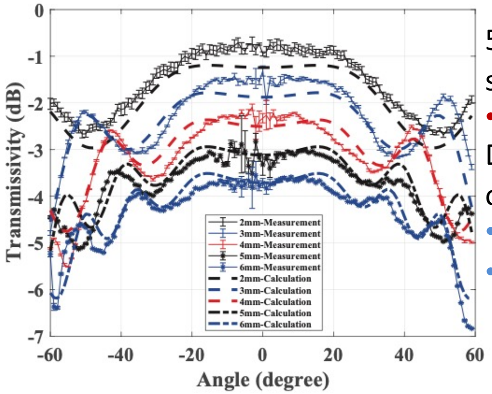


11 pieces of samples:
- Bumpers
- Headlight cover

Different variables of x-axis:
- Frequency
- Incident angle

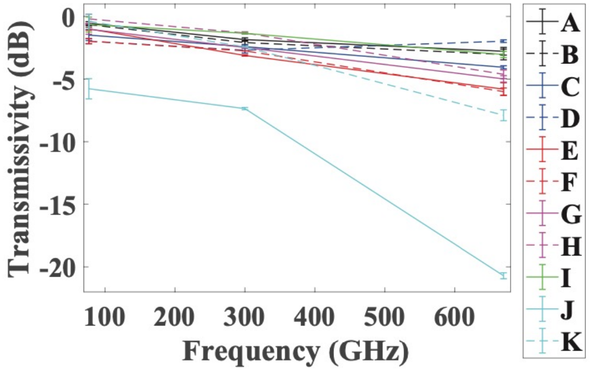
Simulated and measured transmissivities of automotive bumper



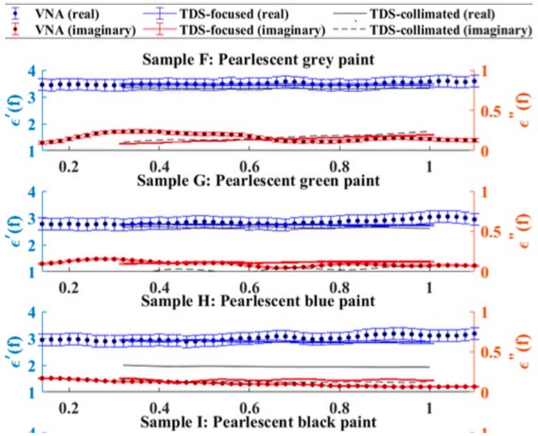
5 pieces of PC sheets:
- 2mm-6mm

Different variables of x-axis:
- Frequency
- Incident angle

Measured and simulated transmissivities through PC sheets with different thicknesses



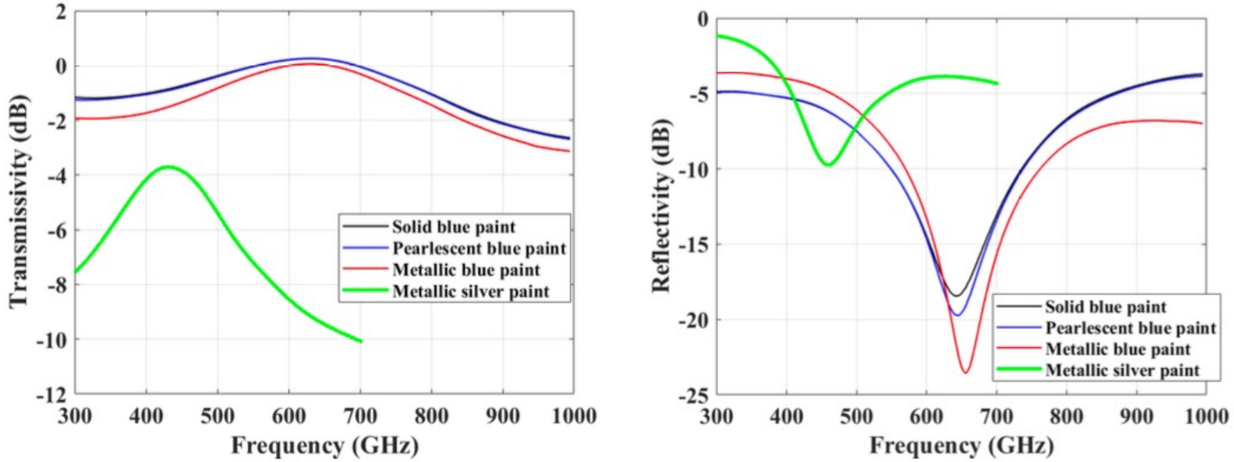
Summary of the transmissivity at 0◦ incidence of the vehicle samples.



21 pieces of samples:
- Solid paints
- Metallic paints
- Pearlescent paints
- Primer
- Clear coat

Frequency bands:
- 0.14THz-1.1THz

Measured CP of pearlescent automotive paints based on THz-TDS and THz- VNA.



Calculated transmissivity and reflectivity of automotive paint in three- layer structure.

Contributions of Part I

- Theory:
  - The theoretical model of the transmissivity of low-THz radar signal through vehicle infrastructure enable the prediction of propagation property in automotive design.
- Experiment:
  - The experimental verification of modeled transmissivity of low-THz radar signal through vehicle infrastructure.
  - The measurement on complex permittivities (CPs) of various commercial automotive paints using THz-TDS and THz-VNA.
- Results:
  - The transmissivity of various automotive components and PC sheets among the frequency bands of 77 GHz, 300 GHz, and 670 GHz.
  - The measured CPs of various automotive paints in different color.
  - All the above results provide non-trivial insights to estimate the capability of range measurement of the low-THz radar system.

Motivation of study on Image Segmentation on Automotive Radar Imagery

Frame fusion of automotive radar image segmentation to improve the segmentation performance

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Moving target indication (MTI)

Image segmentation on automotive radar maps

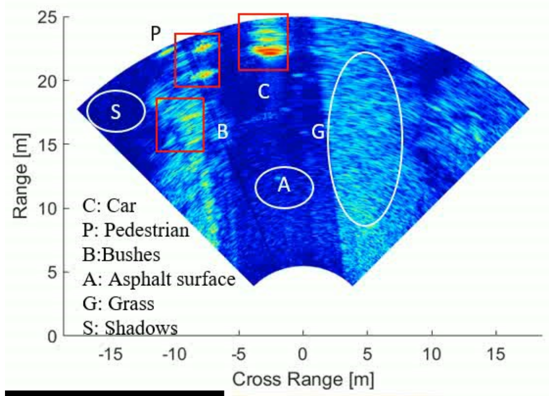
Utilize mm-wave and sub-THz radar → Allows high resolution and high sensitivity automotive radar imagery → Provide imagery for full deep scene reconstruction

Image segmentation

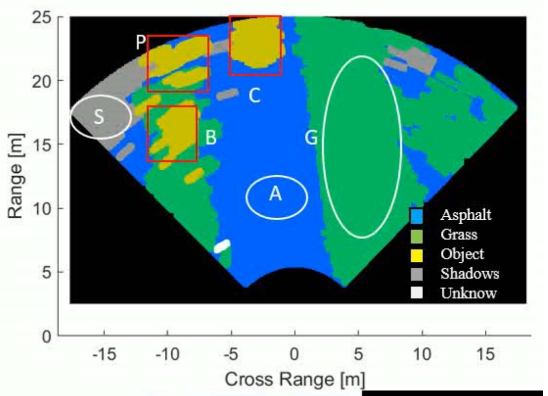
Segment image and classify the surfaces and objects → Identify the passable region → Autonomous path planning and obstacle avoidance

Instances of automotive radar image segmentation

Automotive radar map



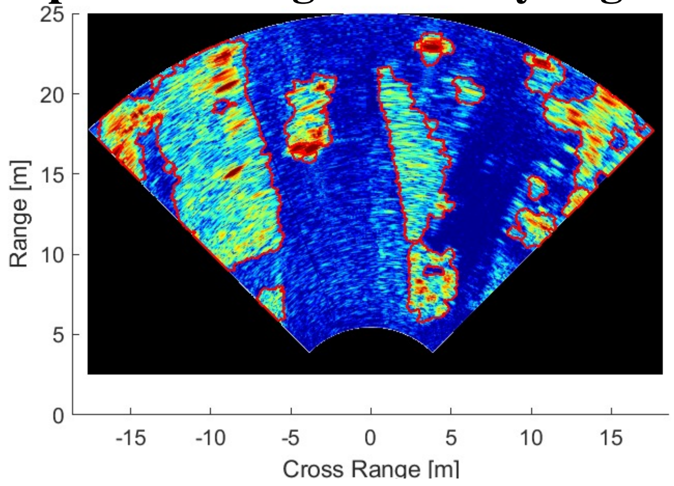
Segmented radar map

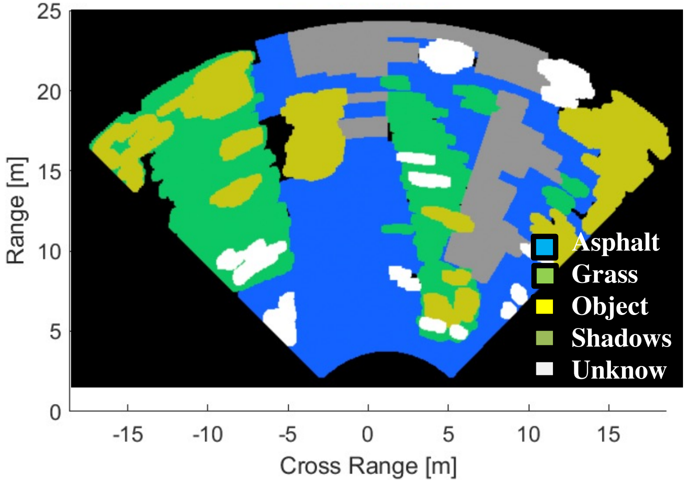


Segmented optical imagery using Mask-RCNN

Single Frame Segmentation – Hybrid Method

Image ROI creation for the classifier has been accomplished using the Canny edge detection

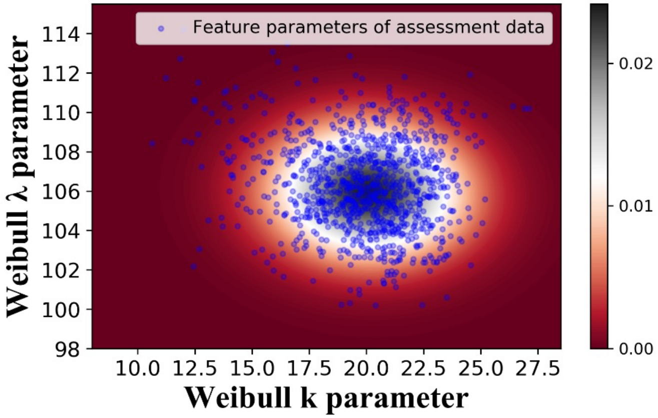




Segmented radar map after region classification using MGD classifier.

MGD classifier in [1]

Example: Bi-variate Gaussian PDF for Asphalt



Supervised classification method using the MGD model

- Distribution features are the variates

Classifier trained using distribution features to form estimates of the mean vector and covariance matrix

- One MGD is trained per class

Input test vector of features into each class MGD

- Obtain probability that the test data belongs to each class

Jaccard Similarity Co-efficient Estimation

$$J_{class} = \frac{A_{fs} \cap A_{label}}{A_{label}}$$

Areas	Asphalt	Grass	Shadows	Objects
Average JSC	0.81	0.64	0.79	0.64

A_{fs} is the correctly classified pixels;
A_{label} is the labeled pixels.

Frame Fusion based on Kalman Filter and Frame Registration – Improve the Segmentation Performance

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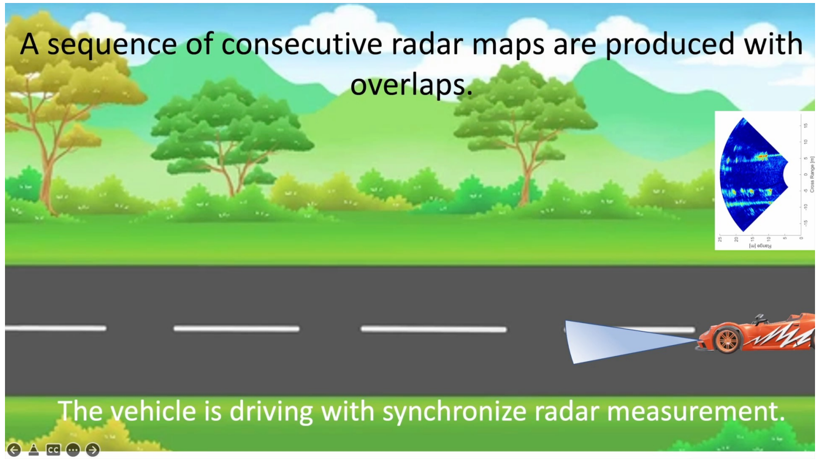
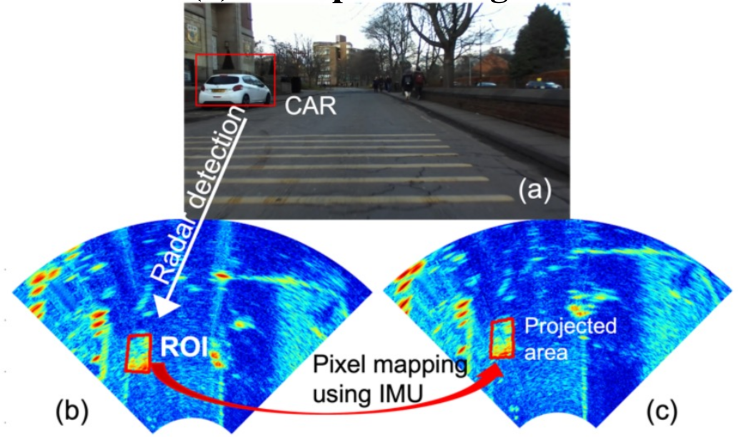
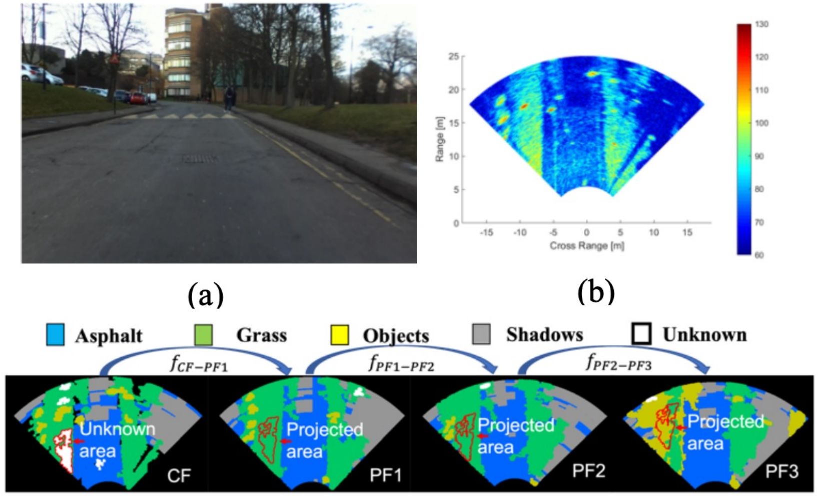


(a) The optical image



(b) The previous frame with ROI **(c) The current frame with projected area**



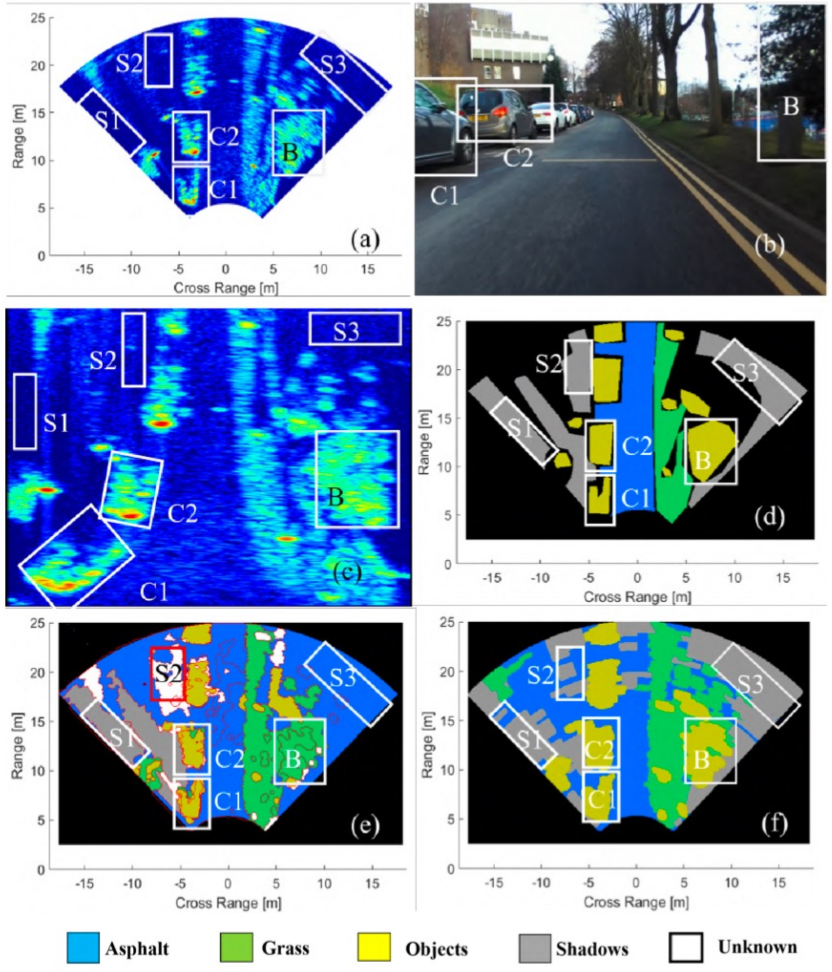
Tracking of specific area for Kalman filter frame fusion

Jaccard Similarity Co-efficient Estimation

$$J_{class} = \frac{A_{fs} \cap A_{label}}{A_{label}}$$

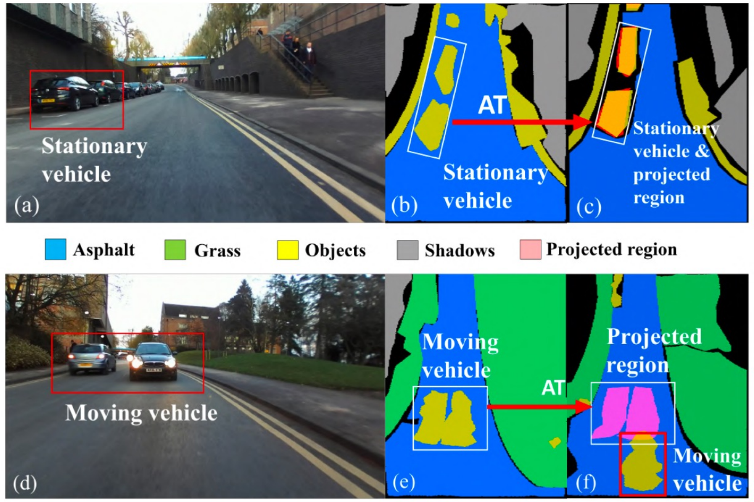
A_{fs} is the correctly classified pixels;
A_{label} is the labeled pixels.

	Asphalt	Grass	Shadows	Objects
JSC_{single}	0.81	0.64	0.79	0.64
$JSC_{multiple}$	0.82	0.85	0.8	0.84

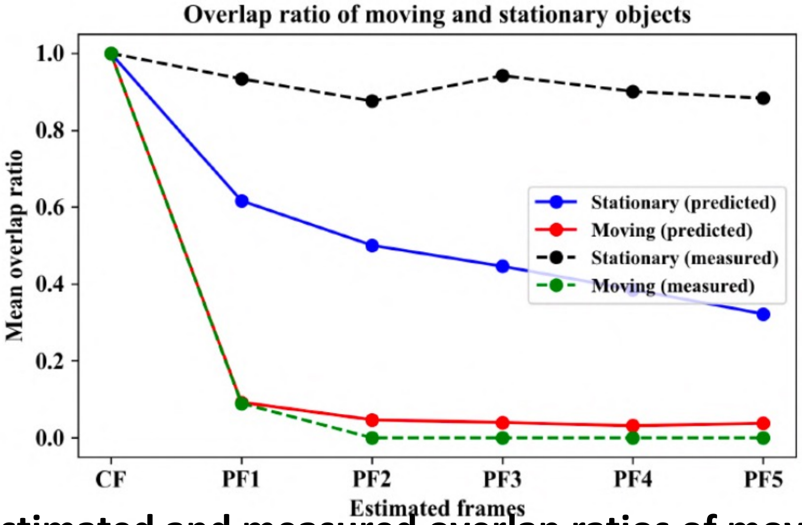


Example of segmentation results before and after frame fusion.

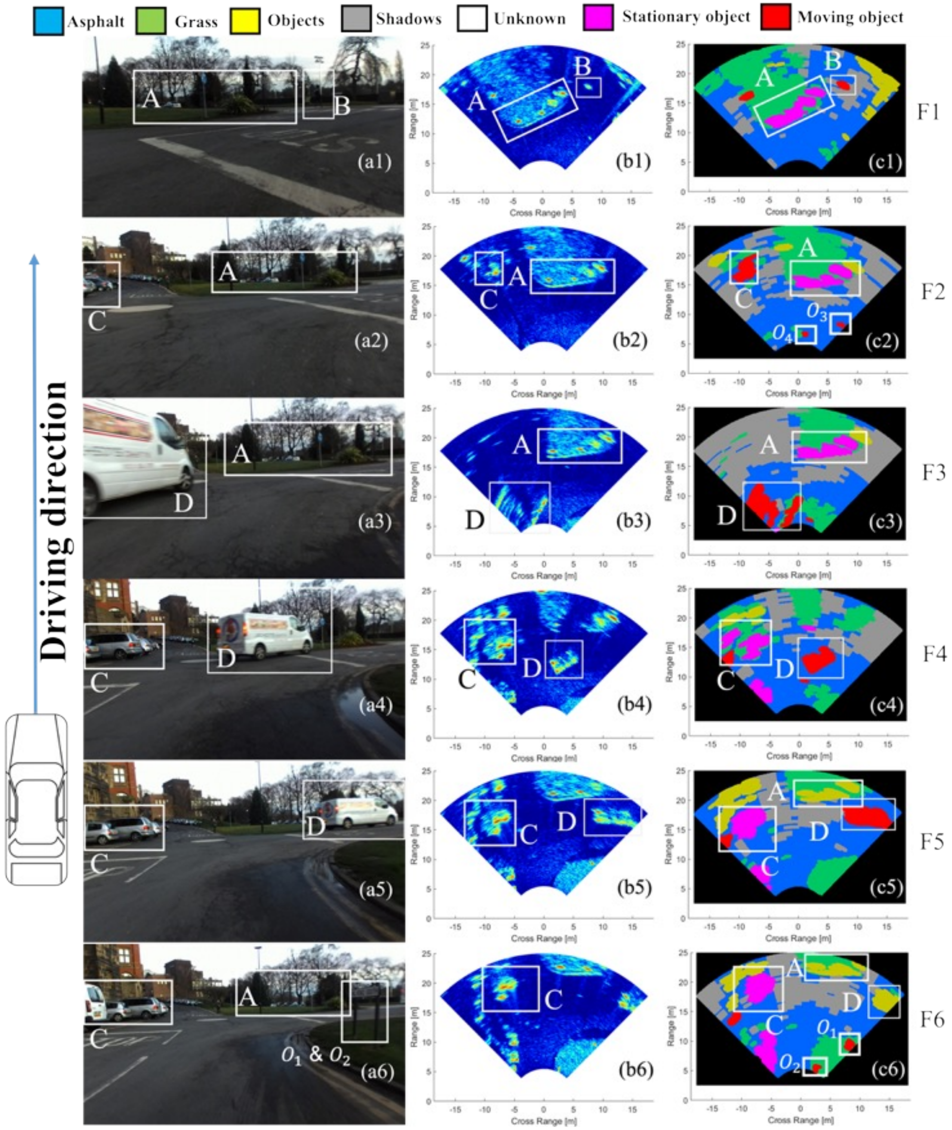
MTI based on Frame-to-Frame Association



Overlap feature difference between stationary and moving objects.



The estimated and measured overlap ratios of moving and stationary objects over CF and PFs.



The segmentation results after the implementation of MTI based on F2FA.

Contributions of Part II

- Single frame segmentation:
  - Feature extraction for each class of road actor/surface by assessing the statistical distribution parameters;
  - Region classification based on the multi-variate Gaussian Distribution (MGD) classifier
  - Hybrid segmentation algorithm combined with pre-segmentation and region classification.
- Frame to frame association:
  - Frame fusion based on Kalman Filter and Frame Registration – Improve the Segmentation Performance
  - Achievement of MTI using frame-to-frame association.

Highly appreciated to your kind listening!