The 42nd Annual Asphalt Paving Conference, Charleston, WV
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Machine Vision-Based Sensing and Analytics for Intelligent Compaction and Tack Coat Inspection

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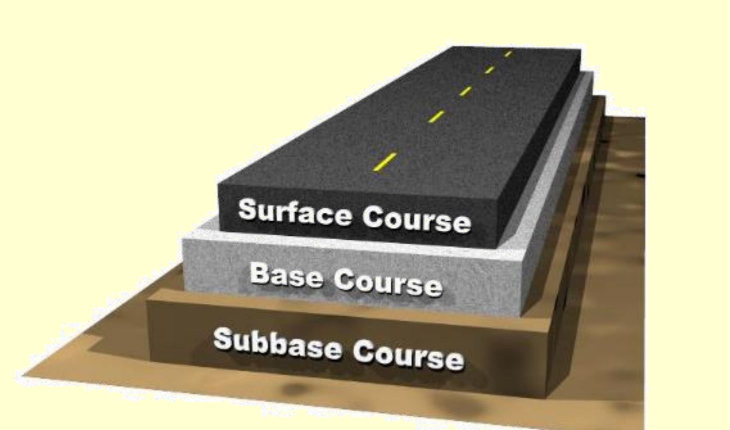
Machine Vision for Intelligent Compaction

AC Pavement Compaction

Aggregates (92%-96%)

Asphalt (4%-8%)

Air



Paving

- The number of roller passes
- The starting and the end point of each pass
- The total number of coverages

Roller Compaction

Pavement Failures

Too Much Compaction

Bleeding and Rutting

Cracking

Too Little Compaction

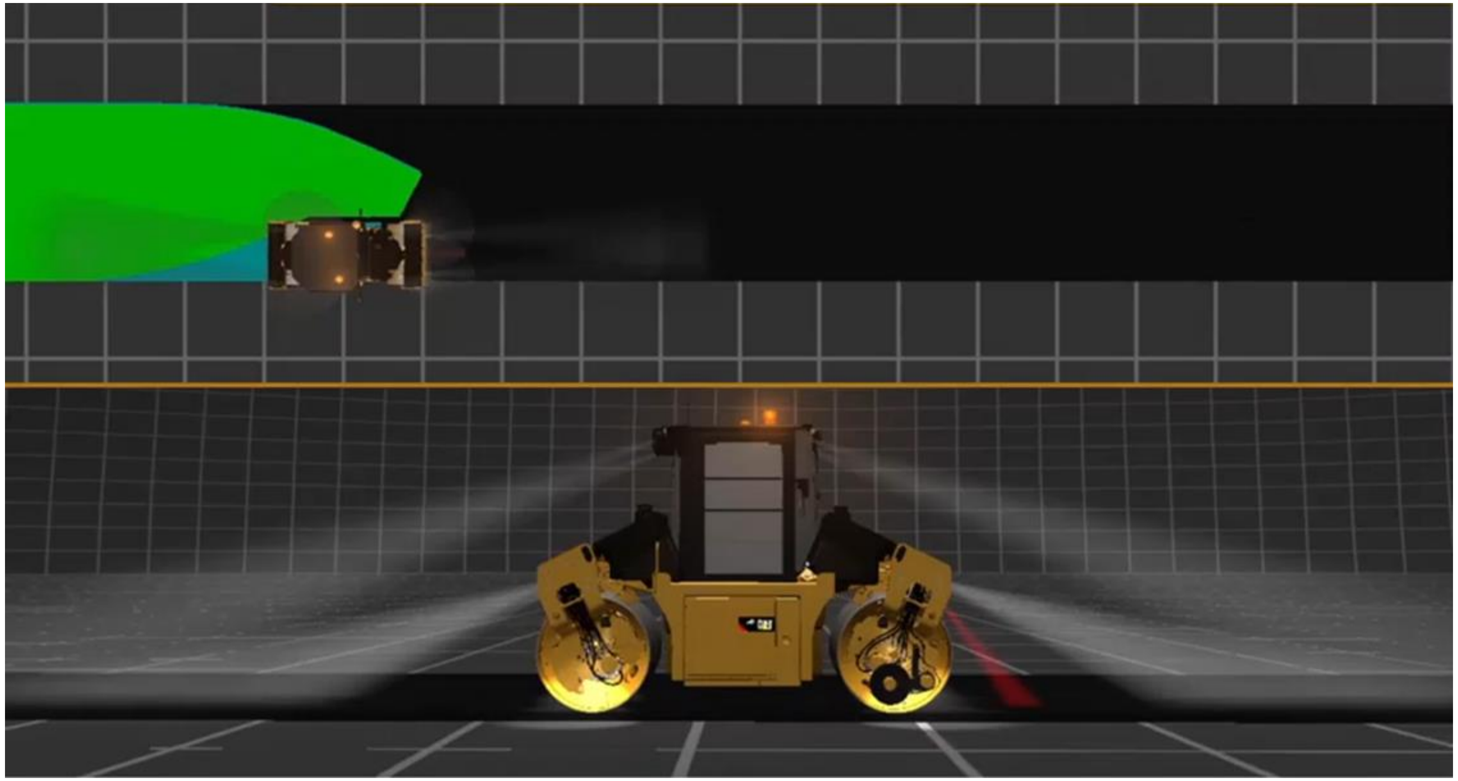
Potholes

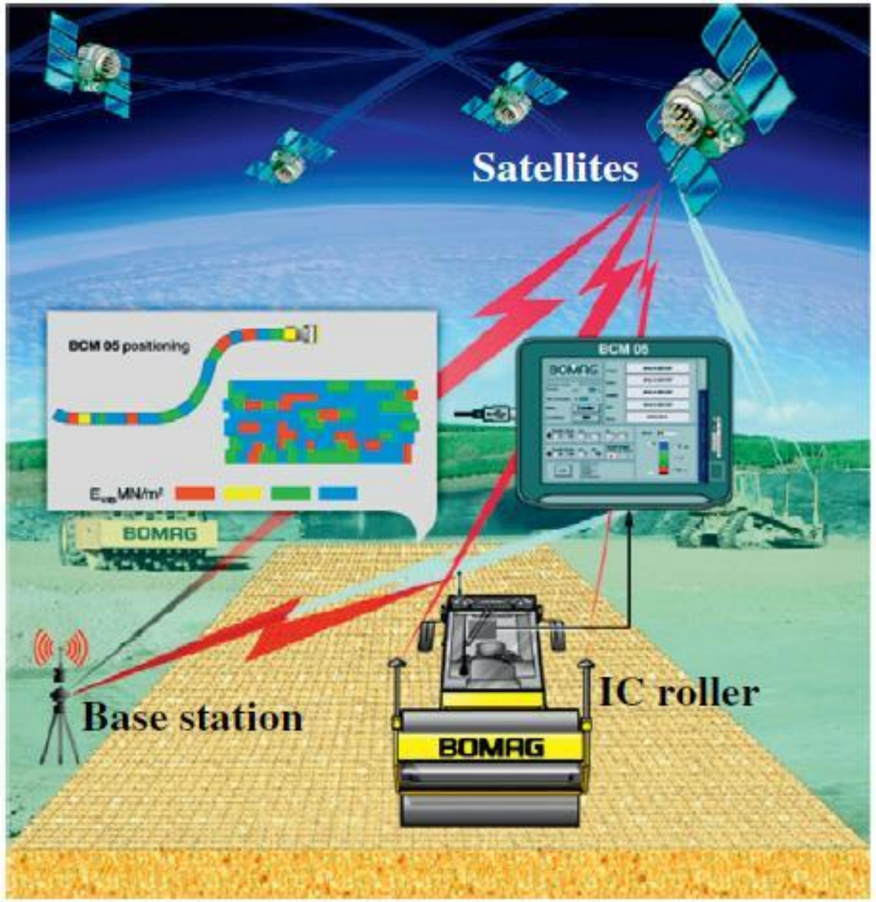
Can we track a roller pattern in pavement compaction operations?

- From Owners' Perspective
  - Evidence
  - Ensure operations meet requirements

- From Contractors' Perspective
  - Evidence
  - Prove operations meet requirements

Intelligent Compaction (IC)

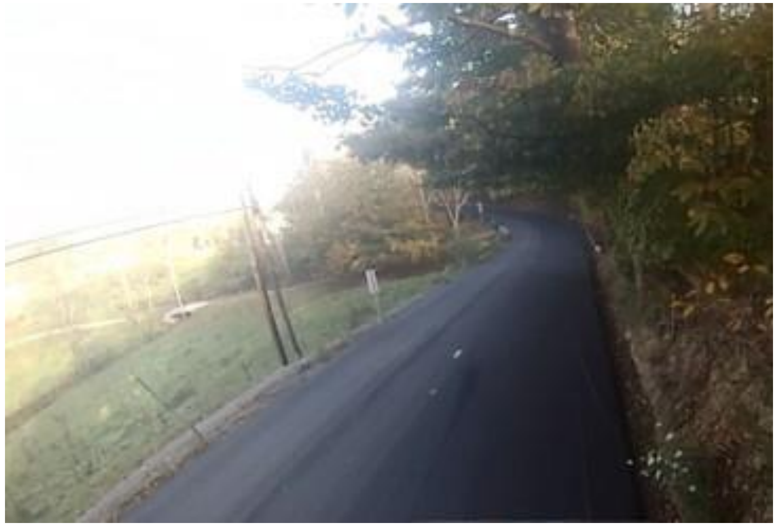




BUT High Cost
Signal Disturbance

BOMAG FAYAT GROUP CAT CATERPILLAR DYNAPAC FAYAT GROUP Sakai

Opportunity



Optical Image

Day & Night

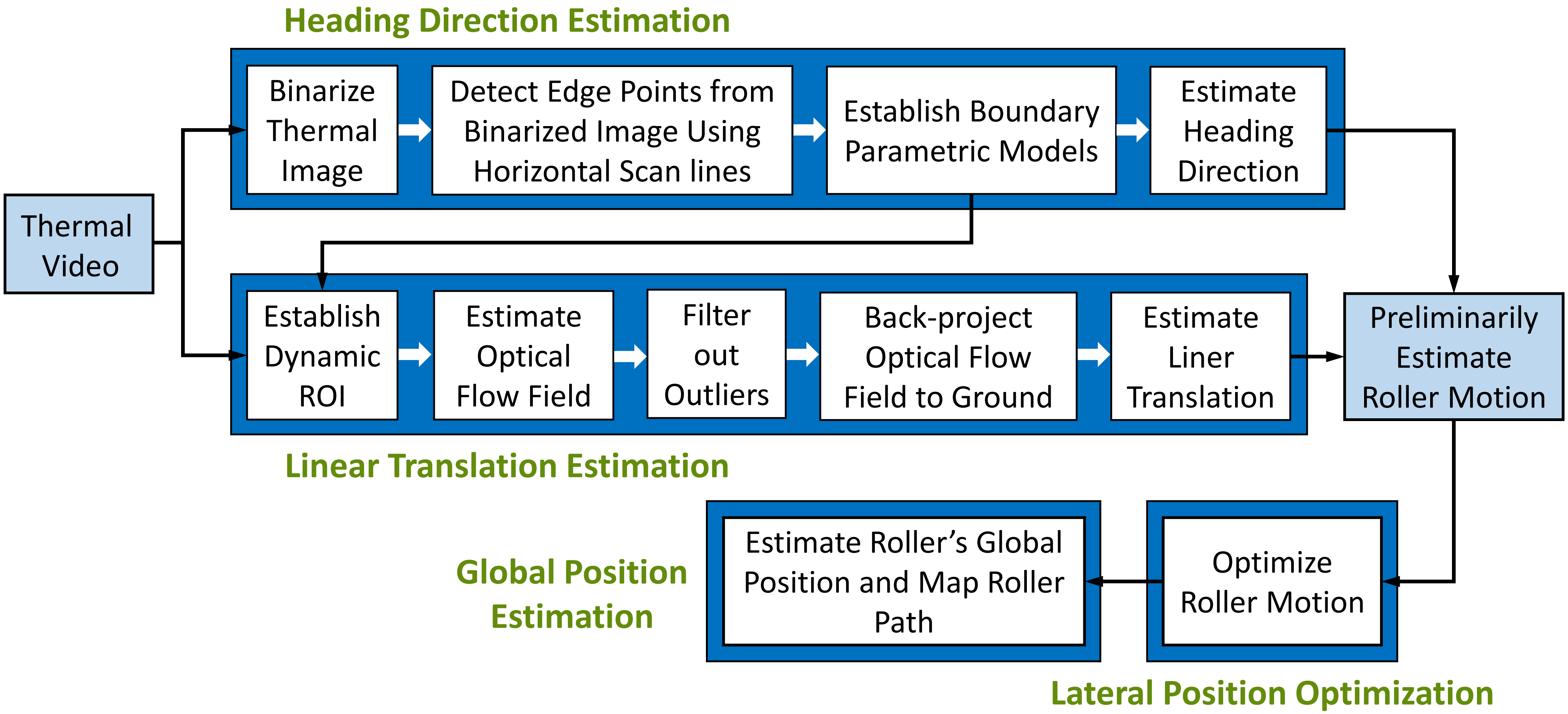
Thermal Image

Day & Night

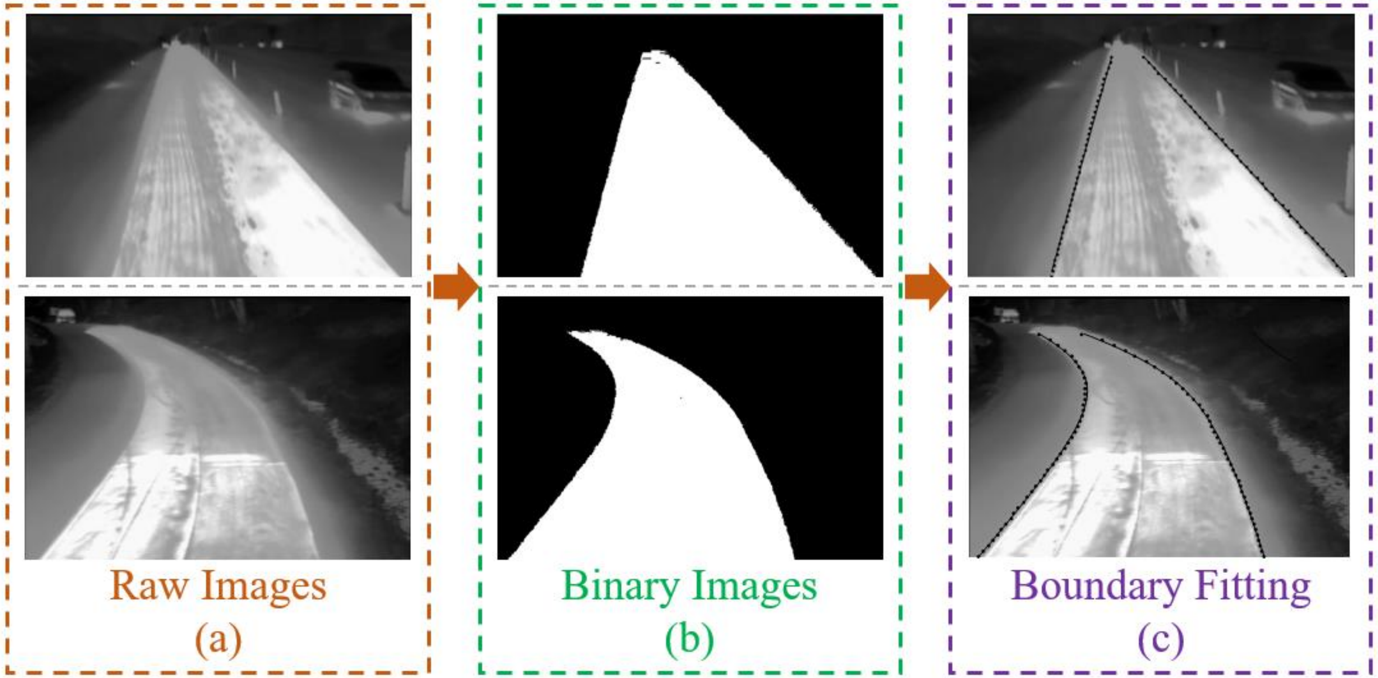
Objective

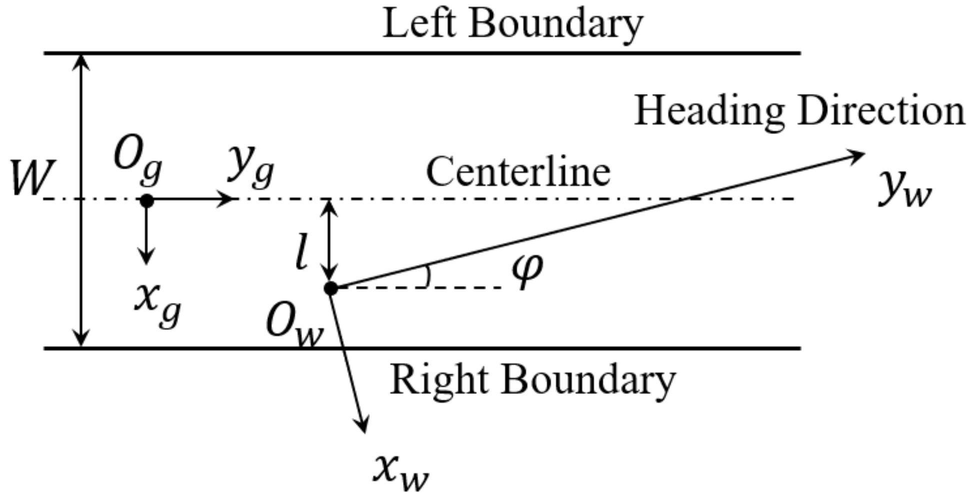
- To develop thermal imaging-based technology for automatic tracking and mapping of paths for economical, real-time roller control in pavement compaction operations

Proposed Overall Framework



Heading Direction Estimation

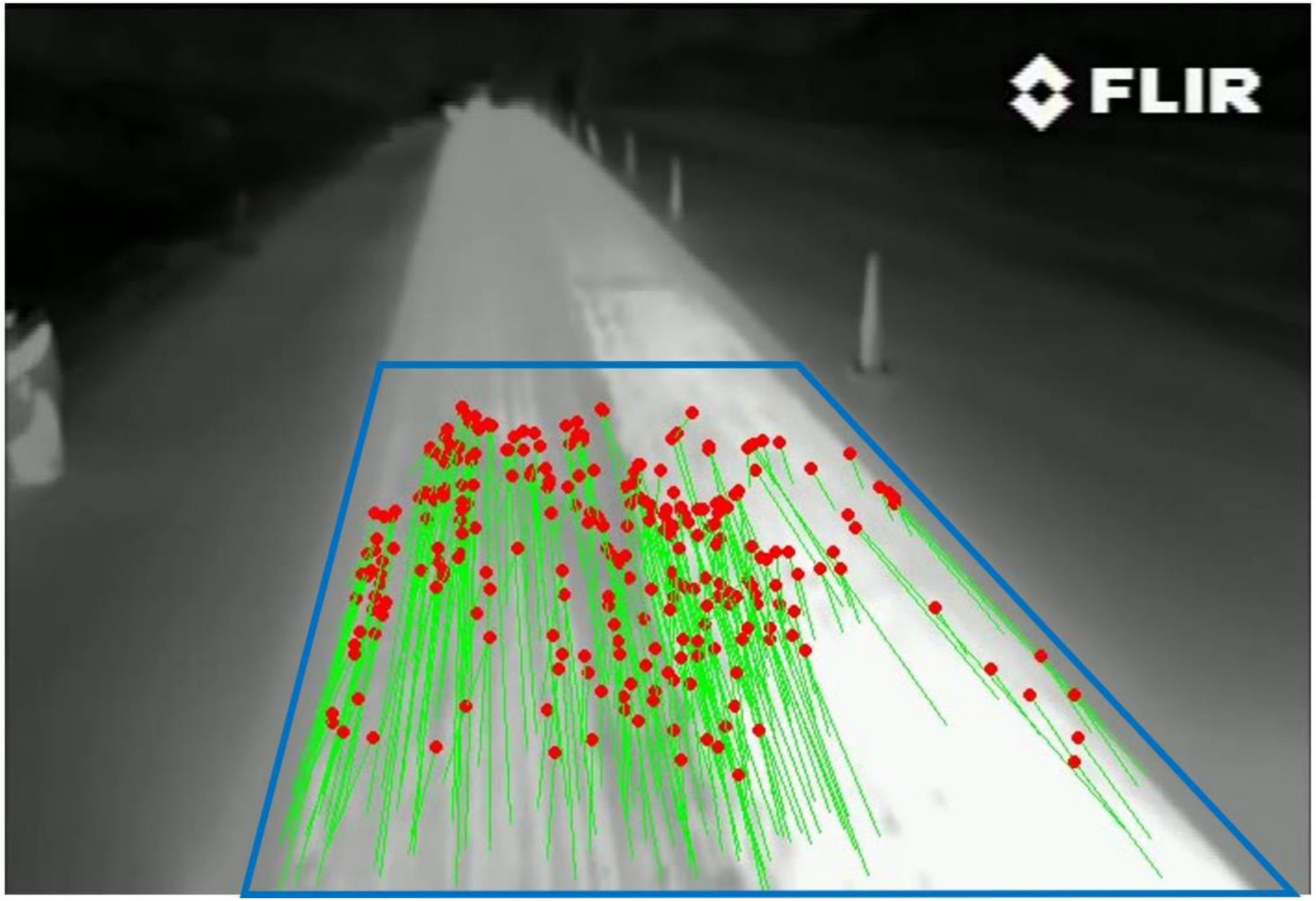




$$ax + by + c + dx^2 + exy + fy^2 = 0 \quad (1)$$

$$\varphi = \begin{cases} -\frac{\pi}{2} + \arctan(-\frac{a}{b}), & \frac{a}{b} \leq 0 \\ \frac{\pi}{2} + \arctan(-\frac{a}{b}), & \frac{a}{b} > 0 \end{cases} \quad (2)$$

Linear Translation Estimation

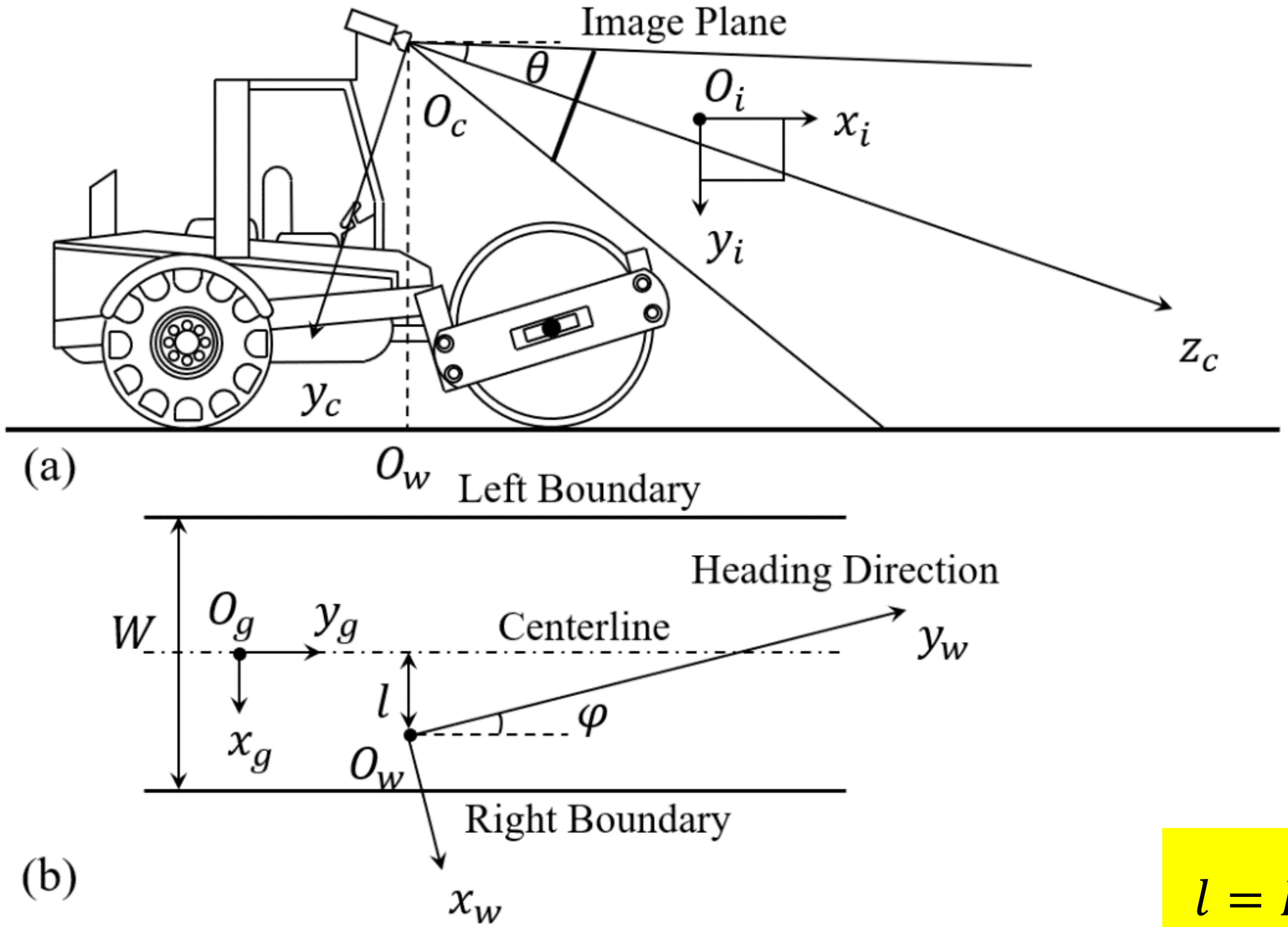


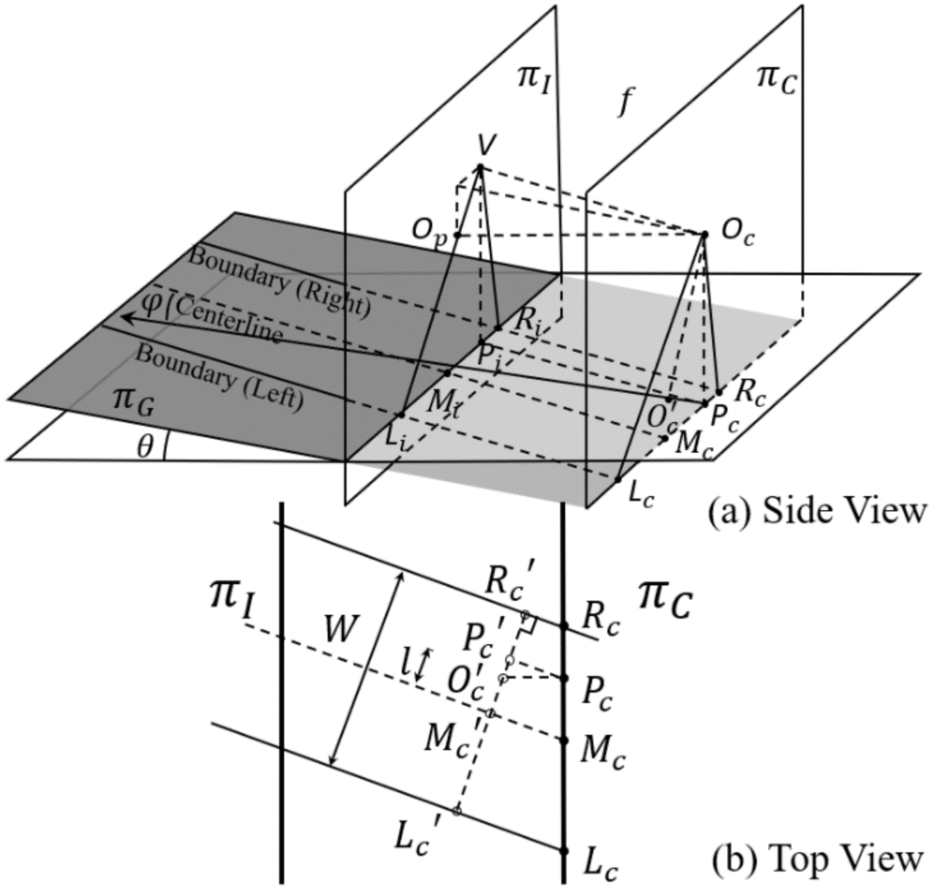
$$\nabla I \cdot \boldsymbol{d} + I_t = 0 \qquad (1)$$

$$\boldsymbol{d} = -\left(\int_S \omega \nabla I^T \nabla I\right)^{-1} \int_S \omega \nabla I^T I_t \qquad (2)$$

Optical Flow Equation

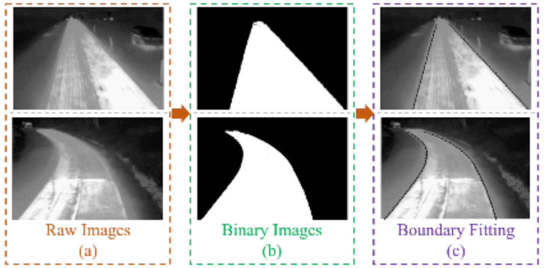
Lateral Position Optimization

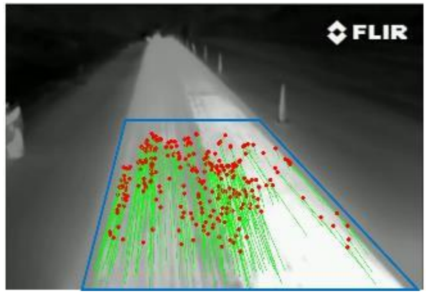


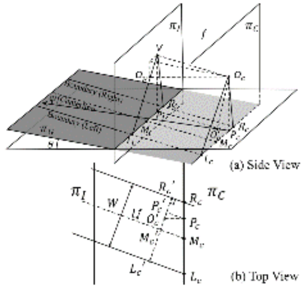


$$l = P_c'M_c' - P_c'O_c' = \frac{a_l + a_r}{2(a_r - a_l)}W - \sin\varphi \cdot \tan\theta \cdot D$$

Global Position Estimation





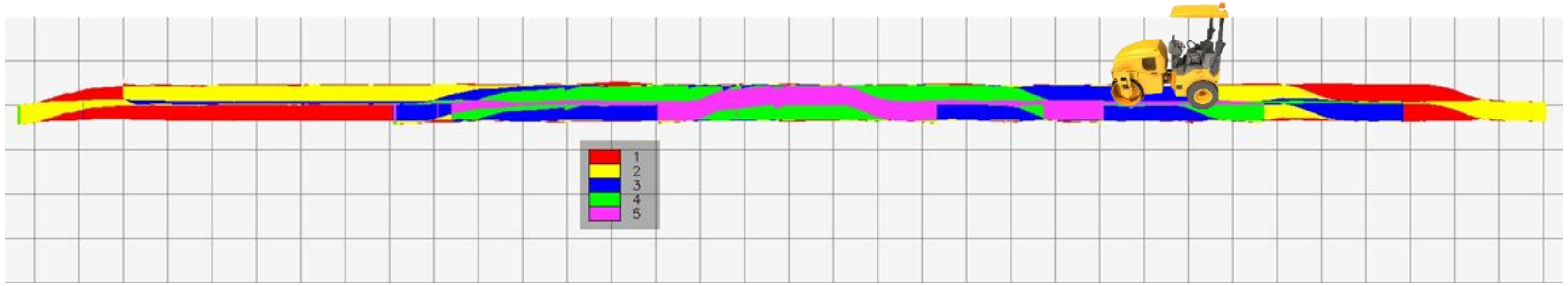


Heading Direction Estimation

Linear Translation Estimation

Offset Distance Estimation

Global Position Estimation

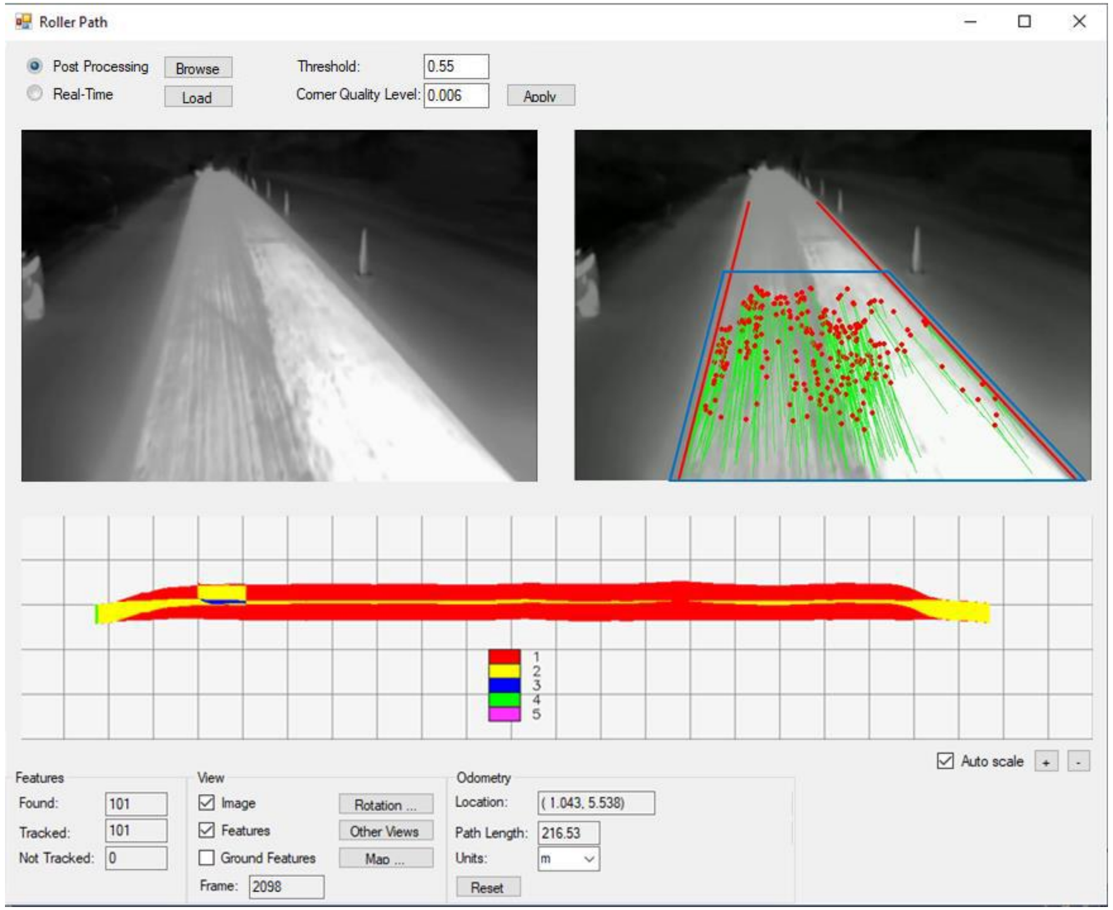


Prototype Development: Hardware

Component	Model	Performance Specification
Infrared Camera	 PathFindIR Camera	Spectral Band: 8-14 m Field of View: 24ºh×18ºv Resolution: 704×480 pixels Focal Length: 19 mm Maximum Frame Rate: 30 fps
Laptop Computer	 ThinkPad X1 Carbon	Processor: Intel® Core™ i5-10210U Processor @1.80 GHz Memory: 16 GB Display Type: 14.0" (1920×1080)
Digital Video Recorder	 Observer™ 4100	Integrated GPS, Wi-Fi, and Ethernet H.264 Video Compression Format Forward-facing RCA Port for Live Viewing on External Monitor
Video Monitor	 SV-LCD70RP	LCD System: 7-inch Resolution: 1400 (RGB)

Prototype Development: Software

- Programming tool
    - Microsoft Visual Studio 2015 and Visual C++
    - OpenCV 3.0 Library

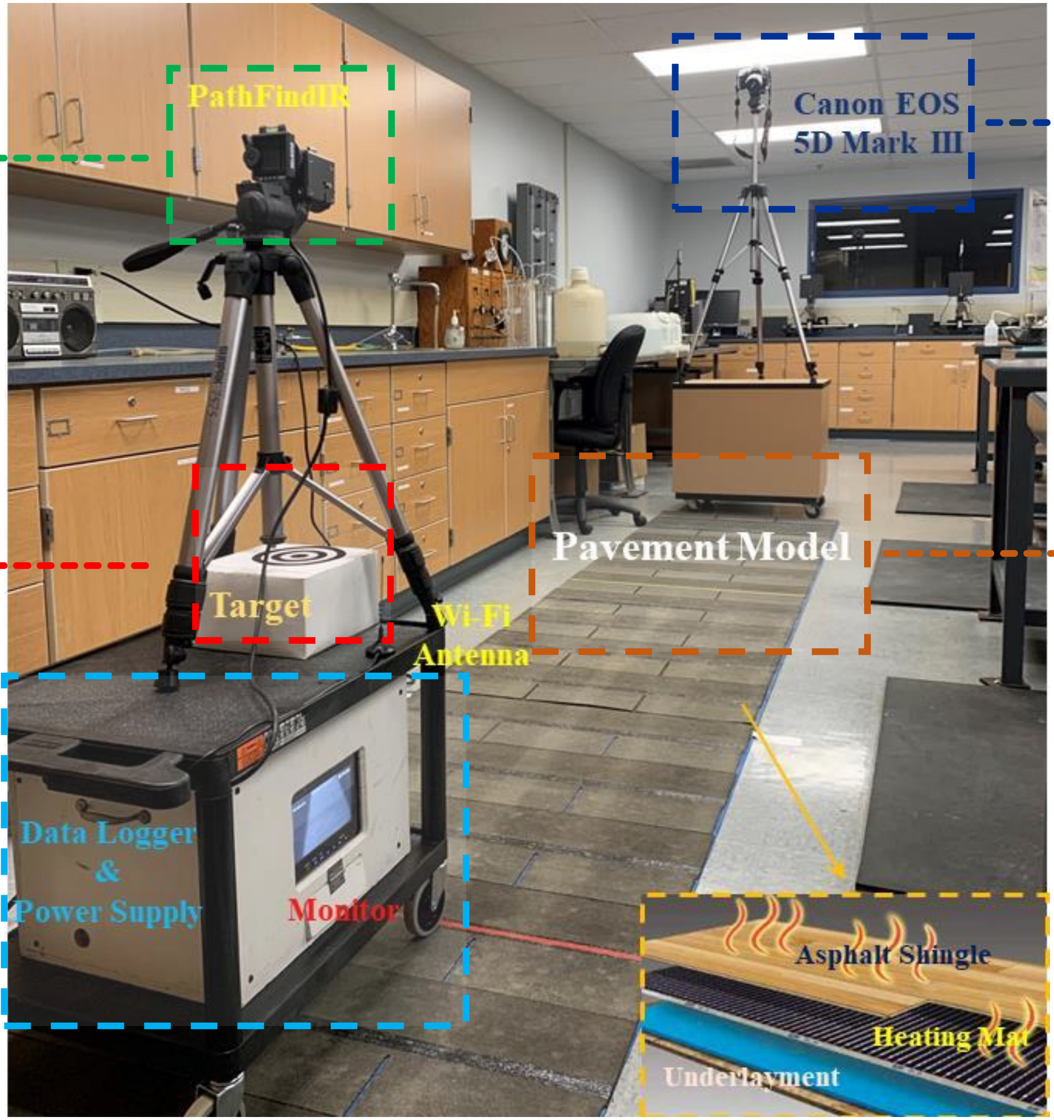


Laboratory Testing

Infrared Camera
Data Collection

Tracking Target
Represent Cart's Location

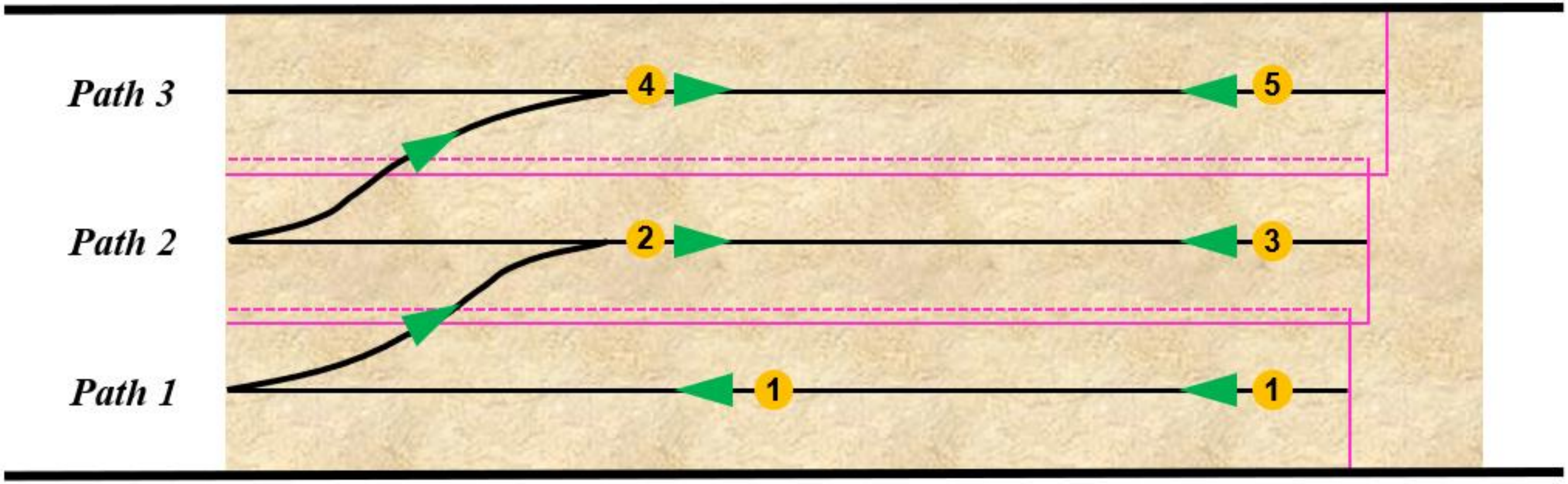
Data Logger
Data Storage and Transmission



Canon Camera
Ground Truth
Trajectory Estimation

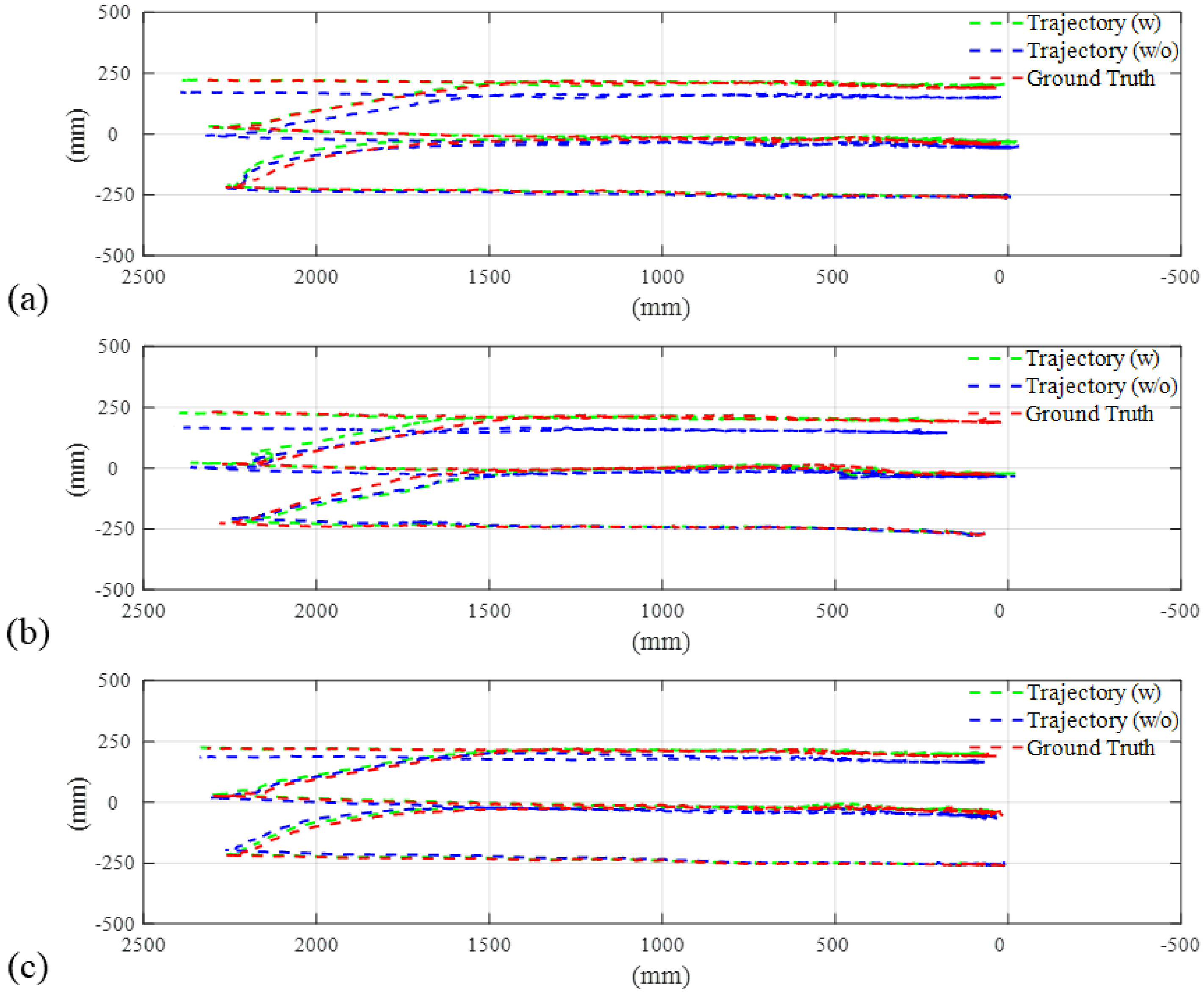
Pavement Model
Asphalt Shingle + Heating Mat
(35^{o}C)

Laboratory Testing



Pre-designed Rolling Pattern in Laboratory Testing

Laboratory Testing



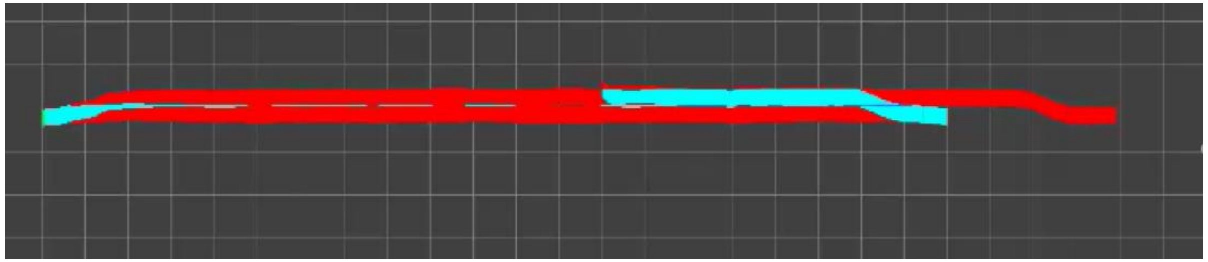
Lateral Direction				
	Mean Absolute Error (mm)		Standard Deviation (mm)	
	w	w/o	w	w/o
Run 1	4.9	24.9	5.1	22.6
Run 2	4.6	29.7	5.5	17.3
Run 3	5.1	18.0	4.4	16.9

Longitudinal Direction		
	Incremental Translational Error (mm)	Cumulative Error Rate (%)
Run 1	65.6	0.538
Run 2	103.9	0.852
Run 3	47.4	0.390

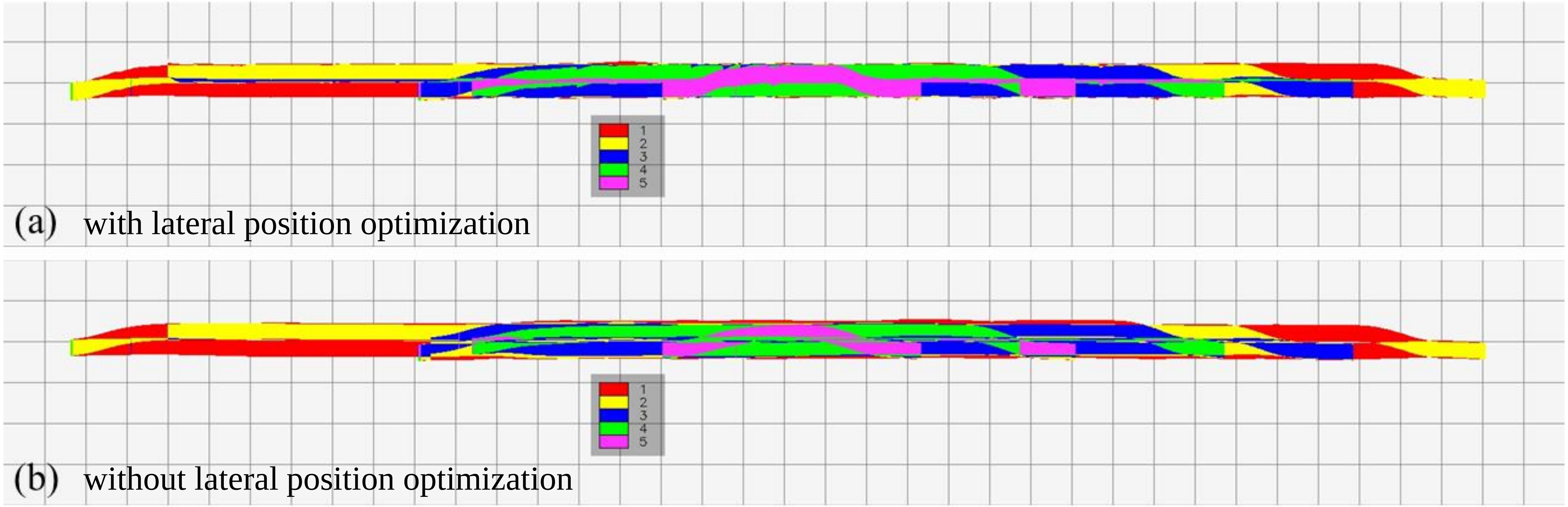
Field Testing

Hot mix asphalt (HMA) pavement on U.S. Route 50, outside Clarksburg, WV

Field Testing



Field Testing



(a) with lateral position optimization

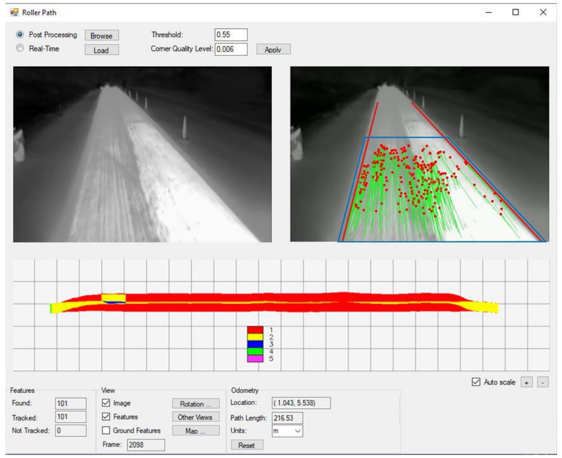
(b) without lateral position optimization

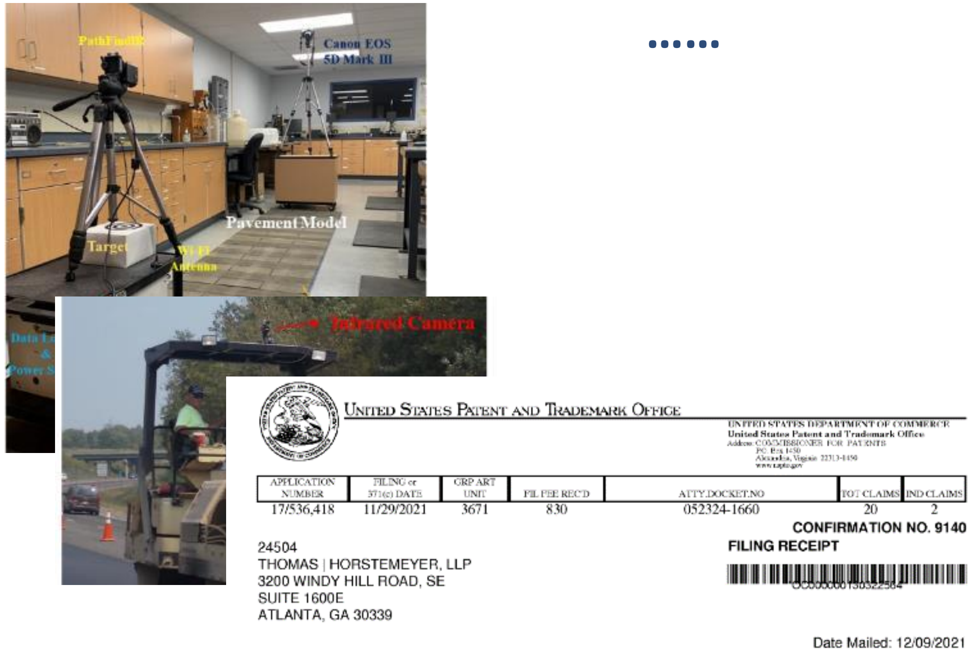
Lateral Direction				Longitudinal Direction	
Mean Absolute Error (cm)		Standard Deviation (cm)		Ground Truth (m)	Estimated (m)
w	w/o	w	w/o	939.7	946.6
3.3	25.8	3.5	29.9	Error	6.9 m (0.7%)

Accuracy of GPS in state-of-art IC roller: **3 cm**

Timeline

2019	2020	2021	2022 and Forward
•Data Collection •Hardware Selection	•Algorithm Development •Provisional Patent Application •Conference Presentation	•Lab/Field Testing •Non-provisional Patent Application •Paper Publication	•Additional Lab/Field Experiments •Economic Assessment •Technology Partnerships ……





Future Work

Laboratory & Field Testing	❑ On non-static roller systems (e.g., vibratory/dynamic rollers) to ascertain system effectiveness in a dynamic environment
	❑ On a range of asphalt layer sizes (width, length, thickness) to validate its ability to evaluate/monitor roller performance
	❑ Optimize system performance/response over ➢ A range of asphalt types (composition, mixtures) ➢ Environmental conditions (asphalt and ambient temperatures, humidity, ultraviolet) ➢ Asphalt grades (horizontal surface through 5%) ➢ Curved asphalt roadbeds
Comparative Economic Assessment	❑ The proposed prototype system vs. commercially available IC system

This cannot happen without help of industry and WVDOH!

Machine Vision for Tack Coat Inspection

What is Tack Coat?

- Tack coat is a thin layer of asphalt that ensures the bonding between an existing pavement and an asphalt overlay
- It is normally used for rehabilitation of constructed asphalt pavements

Severity of the Problem

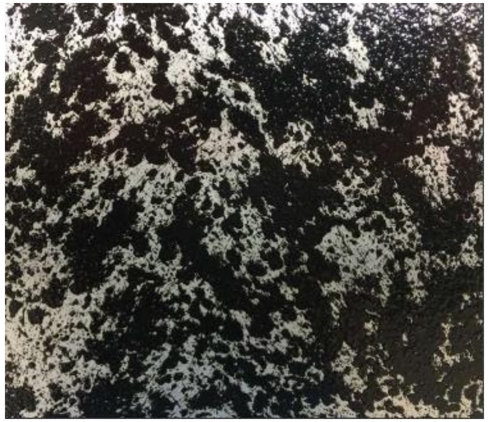
- According to the latest Infrastructure Report Card, 20% of America's pavements are in poor condition
- Our region (Atlantic region) is even worse, with over 22% pavements are in poor condition that need rehabilitation
- Overlays make up large portion of the roadway paving

It Is Important to Apply Tack Coat Uniformly!

- Poor tack coat application may result in inadequate bonding, and later could cause slippage, shoving, and rutting of the overlay.
- Impacts:
  - Inconvenient driving experience of the users
  - Reduced service life of the pavement structure

Tack Coat Inspection

- Visual inspection performed by inspectors from state agencies (state DOTs)
  - Use inspection form to check the quality
  - Assessment of the level of uniformity based on subjective judgment
  - Manual



Non-uniform

Uniform

West Virginia Department of Transportation
Division of Highways
Inspector's Bituminous Emulsion Tack Worksheet

AUTHORIZATION NO:	PROJECT NO:	ATTACHEMENT TO DWR:
LINE NO:	ITEM NO:	DATE:
PLAN ID:		
CONTRACTOR AND SIGNATURE OF CONTRACTOR REP:		
TICKET NO:	ORIGINAL INVOICE NO:	
MATERIAL TYPE:	SOURCE OF MATERIAL:	

OBSERVATIONS – Comment below if any of the following are not met:

- Traffic Control and Flaggers in place ☐
- Surface temp above 40 degrees F ☐
- Surface clean prior to placement ☐
- Uniform application of tack coat ☐

Existing Pavement Condition	Target Application Rate (gal/yd^2)*	
	Undiluted ☐	Diluted (1:1) ☐
New HMA ☐	0.04 – 0.05	0.08 – 0.10
Oxidized HMA ☐	0.07 – 0.10	0.13 – 0.20
Milled Surface ☐	0.10 – 0.13	0.20 – 0.27
PCC ☐	0.07 – 0.10	0.13 – 0.20

*Undiluted ≈60% Residual Asphalt, Diluted ≈30% Residual Asphalt, all footnotes from Table 408.11 apply.

APPLICATION RATE CHECKS

A	B	C	D	E	F	G	H	I	J
Time	Start Station	End Station	Length (ft) C-B	Width (ft)	Area (yd^2) (DxE)/9	Initial Reading (gal)	Final Reading (gal)	Amount Applied (gal) G-H	Rate (gal/yd^2) I/F

(See handout)

COMMENTS: ______

INSPECTOR: ______

JPZ/TJM 12-23-10

Opportunity to Enhance Tack Coat Inspection w/ UAV

- Unmanned aerial vehicles (UAV) have been widely used in the industry
- In comparison with boots on the ground, UAV offers benefits:
  - Accelerated data collection
  - Enhanced survey accuracy
  - Larger area coverage
  - Access to hard-to-reach locations
- Use of this technology opens pathways towards alleviating the situation of current practice of coat inspection

Affordable Cost
(< $2000)

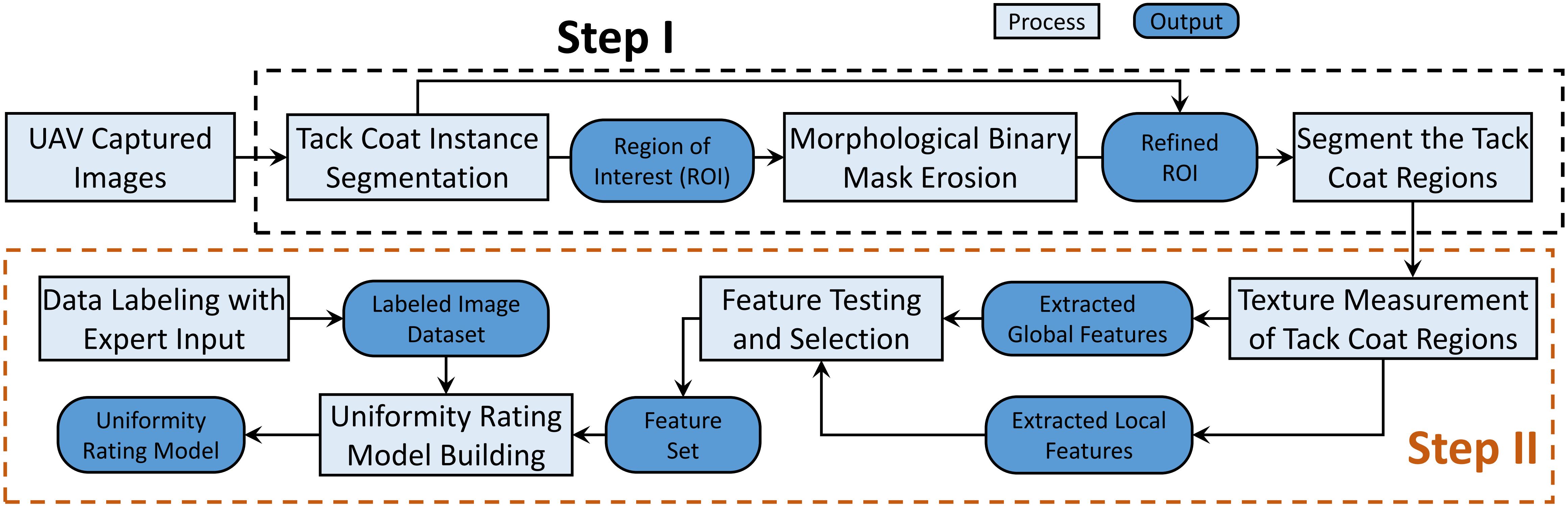
Objective

- To investigate the application of UAV along with machine vision to measure the coverage uniformity of tack coats
  - Efficiently and accurately
  - Measurement conducted on UAV-captured images for decision support

Machine Vision-based Rating Model for Tack Coat Uniformity

Score	Grade
0-59	F
60-69	D
70-79	C
80-89	B
90-100	A

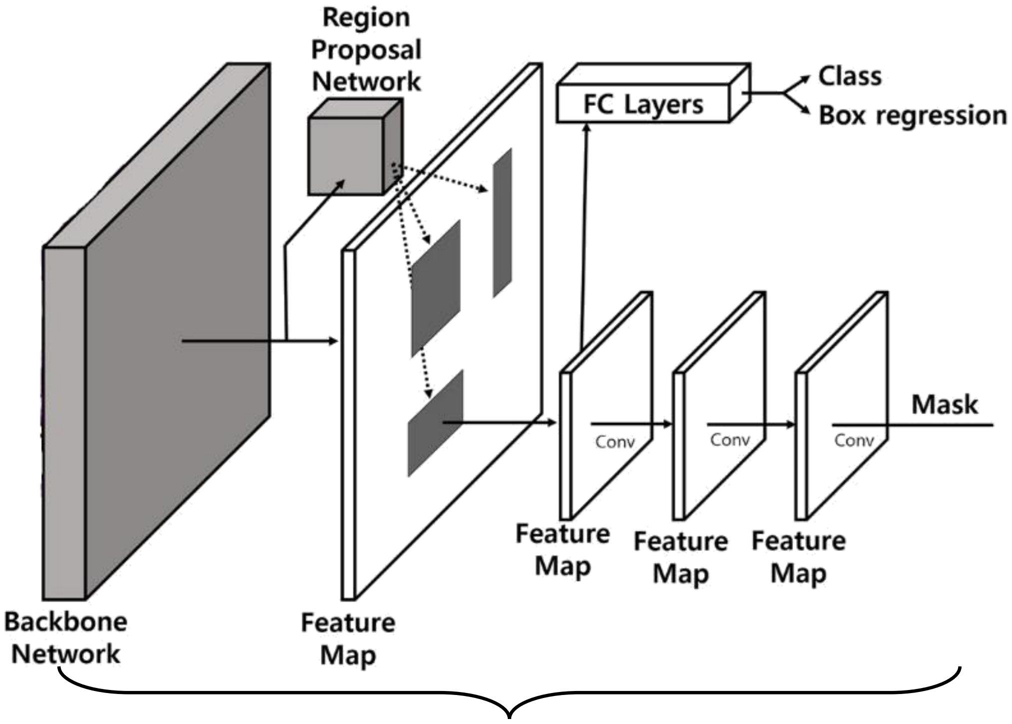
Proposed Overall Framework



- Step I: Tack coat region segmentation and morphological processing
- Step II: Visual feature extraction of tack coats and uniformity rating model building

Tack Coat Instance Segmentation

Input



Mask R-CNN Architecture

Output

Dataset for Model Training

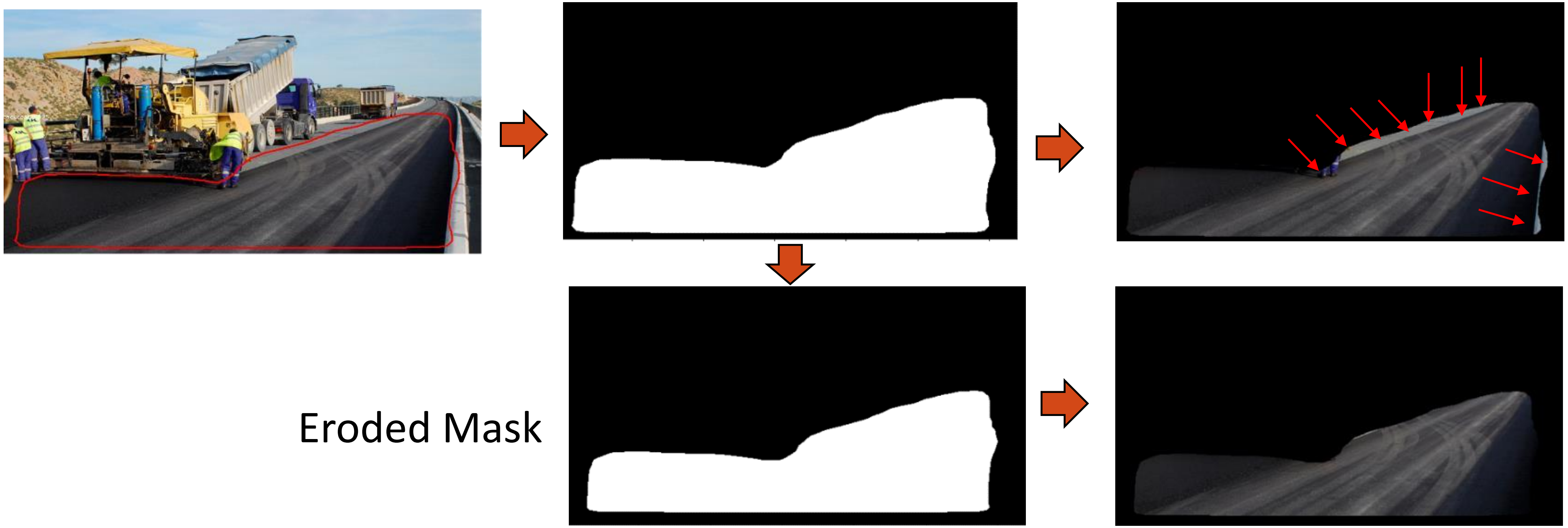
	Image Amount
Training	1774
Validation	220
Total	1994

Mask R-CNN： Class label, Bounding box, Object Contour Line

Faster R-CNN, YOLO, SSD…

Morphological Binary Mask Erosion

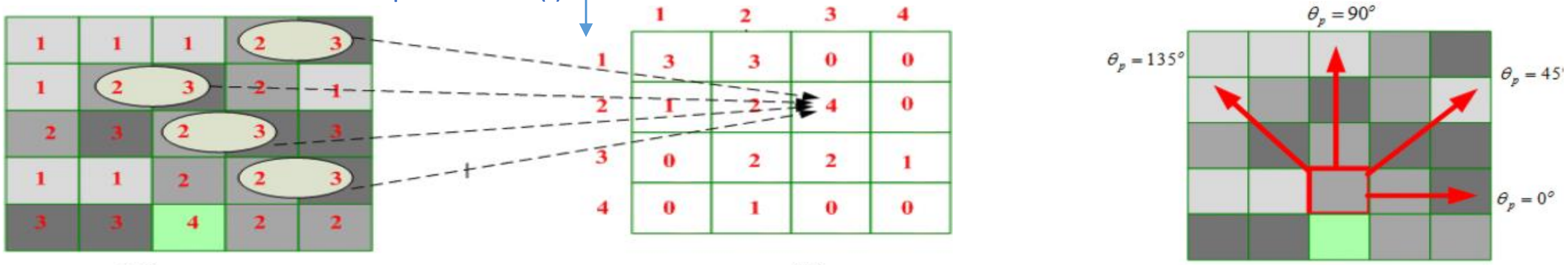
- The binary mask image of the processed region contains false positive (FP) detection
- Apply morphological erosion operation to remove noises on the edges
    - Kernel size (20, 20)



Eroded Mask

Feature Extraction of Tack Coat Regions

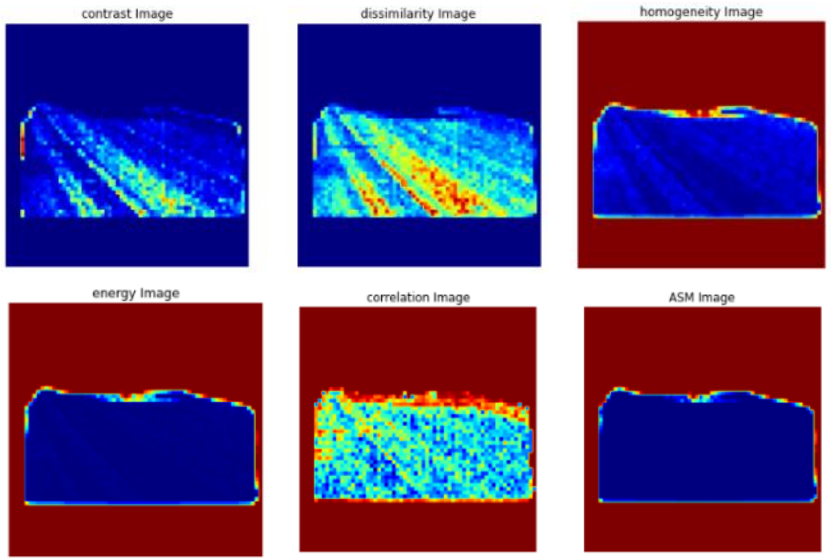
- Grey Level Co-occurrence Matrix (GLCM) is applied to extract second order statistical texture features of the image based on the gray level variations [Fig. (a)]
- Each element (i, j) in GLCM matrix [Fig. (b)] is total of frequency that pixel value i occur in the specified spatial relationship to a pixel value j
  - Element (0, 0) is filtered to exclude the background pixels in calculation
- GLCM matrix is determined by the offset distance and angle between the pixels [Fig. (c)]



(a) (b) (c)

GLCM Features to Depict the Tack Coat Uniformity

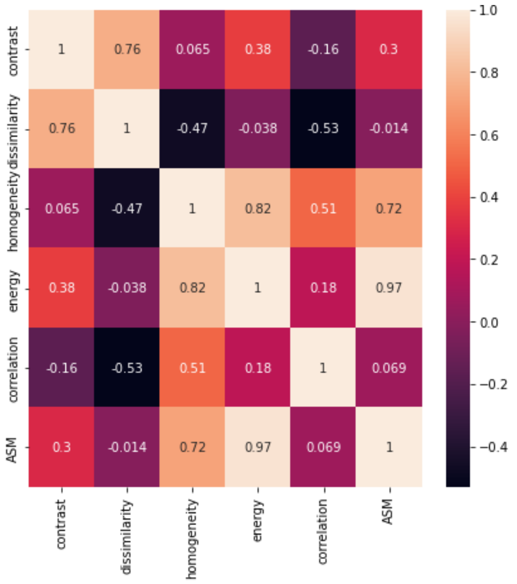
- Six GLCM features generated: contrast, dissimilarity, homogeneity, energy, correlation, and angular second moment
- Global and local GLCM features
  - Feature extraction starts at angle of 0° and offset distance of 1 pixel until image is fully covered
  - It continues w/ increment of 45° and 5 pixels
  - Image is also subdivided for local features extraction at patch size (15, 15) pixels



distance	intensity_mean	intensity_std	contrast	dissimilarity	homogeneity	energy	correlation	ASM
1	22.66322	36.600175	144.929132	9.053013	0.115319	0.019498	0.885342	0.000380
5	22.66322	36.600175	315.078519	13.198390	0.083369	0.016804	0.746803	0.000282
10	22.66322	36.600175	341.600192	13.766356	0.080405	0.016596	0.720938	0.000275
15	22.66322	36.600175	358.796328	14.178582	0.078515	0.016454	0.702857	0.000271
20	22.66322	36.600175	381.545554	14.595381	0.077330	0.016386	0.679318	0.000268
25	22.66322	36.600175	411.428502	15.149834	0.074073	0.016291	0.648152	0.000265
30	22.66322	36.600175	441.276832	15.730540	0.072115	0.016138	0.616198	0.000260
35	22.66322	36.600175	465.882554	16.148058	0.070067	0.016033	0.588424	0.000257
40	22.66322	36.600175	491.158228	16.555889	0.068967	0.015949	0.559097	0.000254
45	22.66322	36.600175	512.560586	16.910048	0.067263	0.015841	0.533981	0.000251
50	22.66322	36.600175	536.812976	17.261712	0.064669	0.015758	0.506411	0.000248
55	22.66322	36.600175	562.206988	17.585067	0.063942	0.015680	0.478515	0.000246
60	22.66322	36.600175	594.307106	18.043244	0.063331	0.015546	0.444072	0.000242
65	22.66322	36.600175	620.051214	18.374518	0.061441	0.015450	0.414826	0.000239
70	22.66322	36.600175	640.708300	18.621022	0.060098	0.015383	0.389470	0.000237
75	22.66322	36.600175	661.117312	18.899127	0.059523	0.015297	0.364566	0.000234
100	22.66322	36.600175	707.895725	19.758458	0.054351	0.014980	0.292721	0.000224

Feature Testing and Selection

- Test and select the feature candidates that depict discriminative patterns
  - Use Pearson correlation matrix to measure the linear correlation of independent variables
    - Value closer to 0, 1, -1 implies weaker, stronger positive and negative correlation, respectively
    - Remove features that are highly correlated (e.g., correlated features to homogeneity, energy = 0.91 and ASM = 0.82)
  - Use back elimination to evaluate the feature performance
    - Select significance level = 5% or P-value = 0.05
    - Features have high significance performance if P-value < 0.05, features with P-value greater than 0.05 are removed



Features	P-value
Contrast	**0.0059**
Dissimilarity	**0.00096**
Homogeneity	0.855
Energy	**0.046**
Correlation	**0.000068**
ASM	0.11

Uniformity Rating Model Building

- Label the image set with tack coat uniformity level
- Apply machine learning algorithm with the selected features to build the model
  - Random forest
  - Support vector machine (SVM)
  - Light gradient boosting machine (LGBM)

Tack Coat Grade
A
B
C

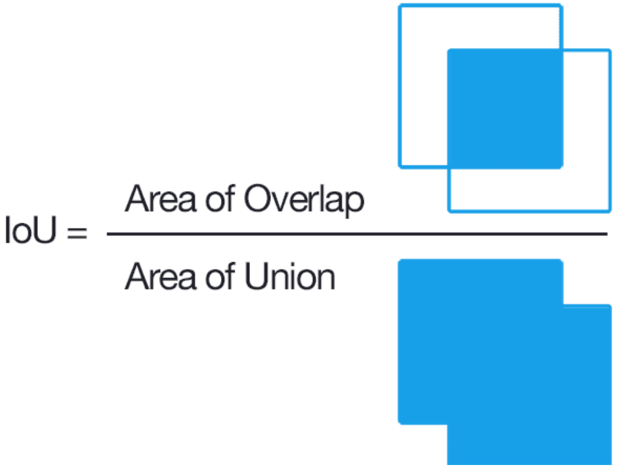
	Image Amount
Training	750
Validation	150
Total	900

Preliminary Results: Tack Coat Instance Segmentation

- Intersection over union (IoU)
  - Green contour = Ground truth
  - Red contour = Predicted region

- Performance evaluation

	Only Mask R-CNN	
	Highest	Mean
IoU	0.93	0.85



Tack Coat Detection by Deep Learning Method (Mask R-CNN)

Preliminary Results: Morphological Binary Mask Erosion

	Only Mask R-CNN		With Erosion	
	Highest	Mean	Highest	Mean
IoU	0.93	0.85	0.95	0.89

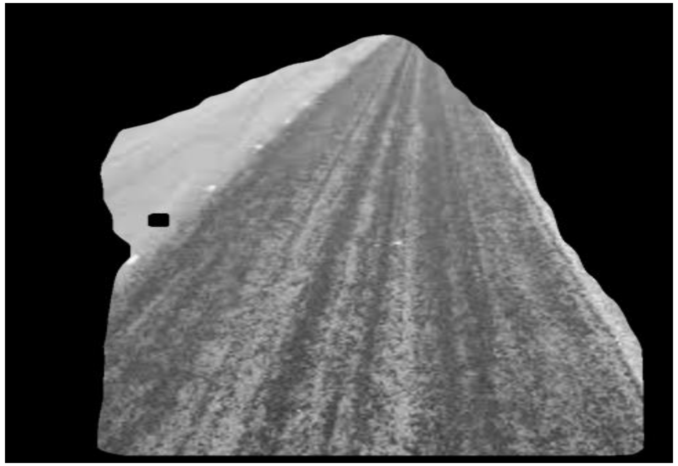
Preliminary Results: Uniformity Rating Model

- The model was first trained with all the 102 features
- Accuracy was improved using 63 discriminative features
  - Using Pearson corelated matrix, 17 highly correlated features were not used
  - Using back elimination method, 22 features w/ P-value > 0.05 were further removed

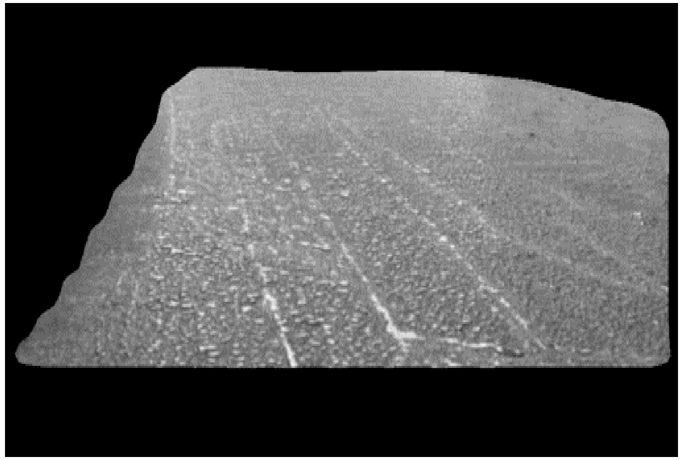
Model	Before Feature Selection			After Feature Selection		
	Correct # Predictions	Total # Predictions	Accuracy	Correct # Predictions	Total # Predictions	Accuracy
RF	108	160	0.68	112	160	0.70
SVM	113	160	0.71	135	160	0.84
LGBM	125	160	0.78	145	160	0.91

Preliminary Results: Uniformity Rating Model

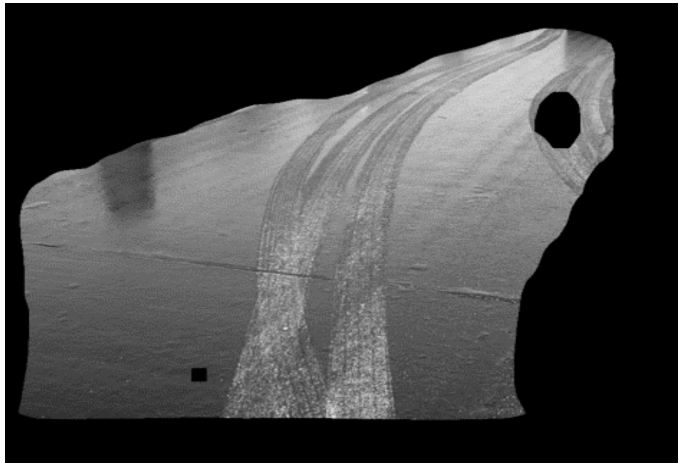
Ground Truth C
Predicted grade C



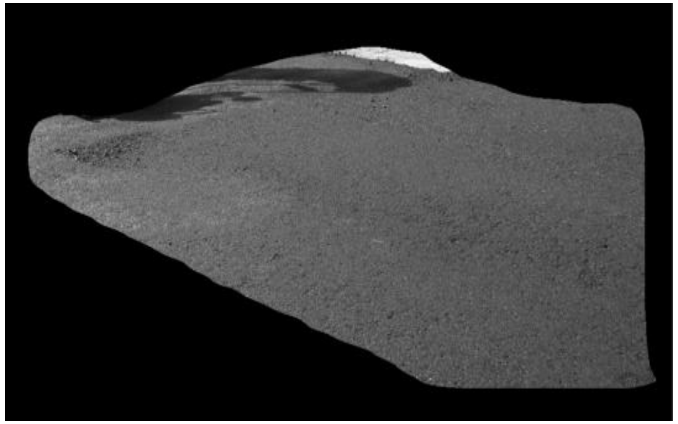
Ground Truth A
Predicted grade A



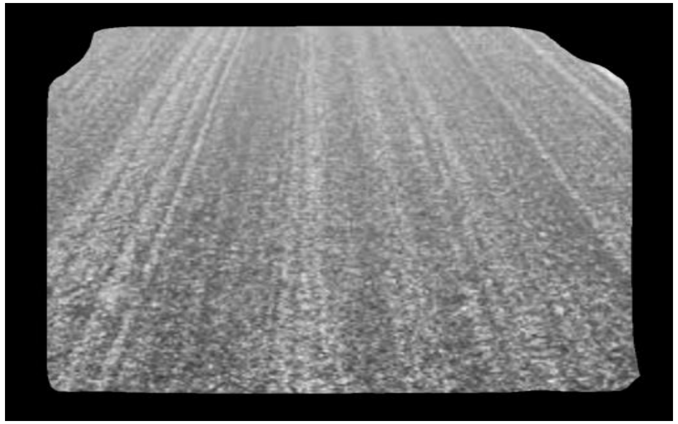
Ground Truth B
Predicted grade B



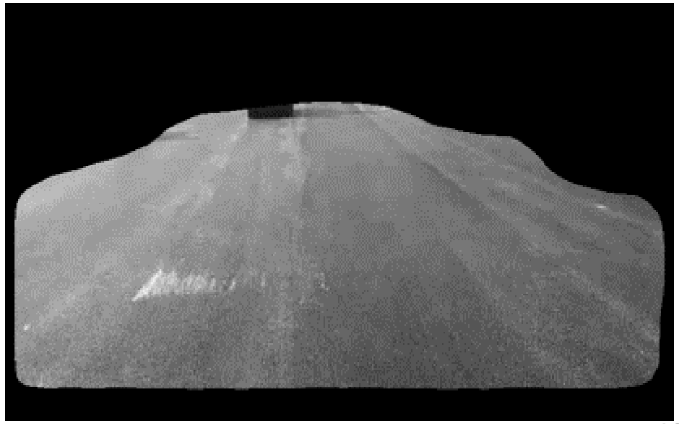
Ground Truth A
Predicted grade A



Ground Truth C
Predicted grade C



Ground Truth A
Predicted grade A



Future Work

- Data collection
  - Increase the dataset to improve the rating model accuracy
    - e.g., use drone to collect tack coat images in the field
- Further testing and evaluation of feature selection methods and training models
- Exploration of methods to localize the uniformity regions

Acknowledgement

- Collaborators

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Thank You! Questions?

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