Autonomous Driving Using Road Surface Measurement

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VICTOR LABORATORY

UNIVERSITY of VIRGINIA

University of Virginia

- Founded by Thomas Jefferson in 1819 and the only UNESCO World Heritage campus in USA
- Ranked most beautiful campus in USA
- One of the hilliest campuses in USA
- 23,000 students (15,000 undergrads / 8,000 grads)
- One of three best public universities

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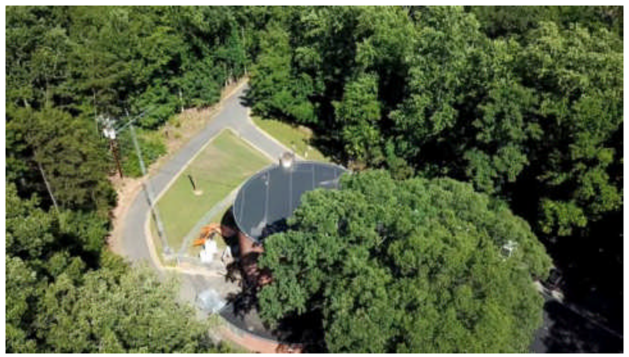
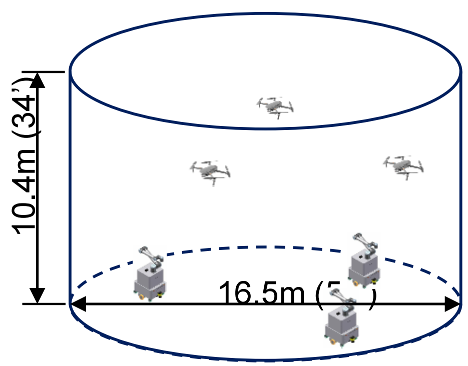
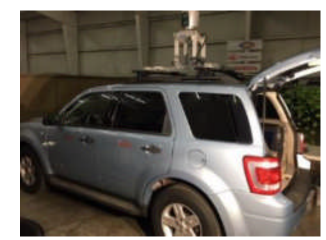
VICTOR (<u>**VI**</u>rginia <u>**C**</u>ooperative au<u>**TO**</u>nomous <u>**R**</u>obots) Laboratory

in 20,000sqf building





Milton test field



Outline

1. History and state-of-the-art of autonomous driving
2. Road surface measurement for autonomous driving
3. Structure-from-motion (SfM) based road surface measurement
4. Autonomous defect identification
5. Autonomous driving using road surface measurement

History of Automated Driving (1990-2007)

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

SfM based road surface measurement

Defect identification

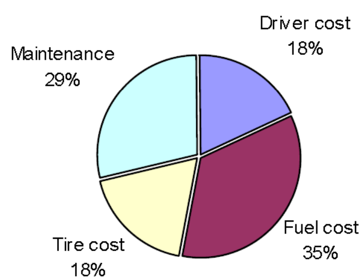
Autonomous driving using road surface measurement

Automated Mining

Autonomous mining vehicle

1990 → 2016

Manual driving
↓
Monitoring from control room
↓
Remote control from control room
↓
Autonomous driving
↓
Fully autonomous driving



Autonomous mining with Komatsu [2000]

Autonomous cargo handling with Patrick [2001]

DARPA Urban Challenge in 2007 and Onwards

Virginia Tech at DARPA Urban Challenge

Rank	University	Time	Av. speed
1	**CMU**	**4:10:20**	**22.53 km/h**
2	**Stanford**	**4:29:28**	**22.05 km/h**
3	**Virginia Tech**	**4:36:38**	**20.92 km/h**
4	MIT	6 hours	-
5	UPenn	Completed	-
6	Cornell	Completed	-

Cruise control: Constant velocity
Adaptive cruise control: Constant distance to the vehicle in front
Automatic Emergency Brake (AEB): Reaction to obstacles in front
Lane Keeping Assist System (LKAS): Lane recognition and automatic steering (In highways and motorways)
Traffic Jam Assist (TJA) system: Integration of AEB and LKAS. Slow automatic speed/steering control on busy roads
…..

USA

- GM:
  - To sell cars that requires no driver and allows autonomous driving until parking at the destination by 2018 [2008]
  - To sell Cadillac with highway autonomous driving system by 2017 [2012]
- Google: Google Driverless Car project [2011]
- Gov't: State law allowing autonomous driving (Nevada [2011], Florida [2012] California [2012])

Level of Driving Automation

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SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver **monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Next Generation Technology in Autonomous Drivingn

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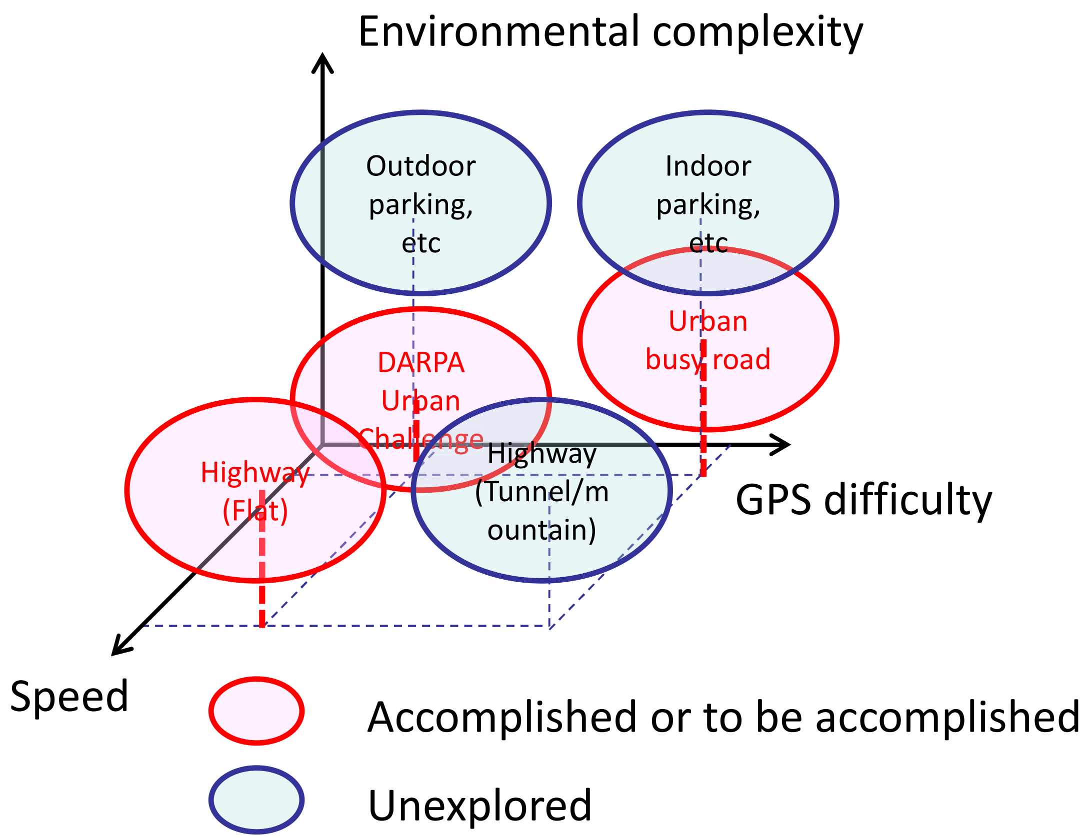
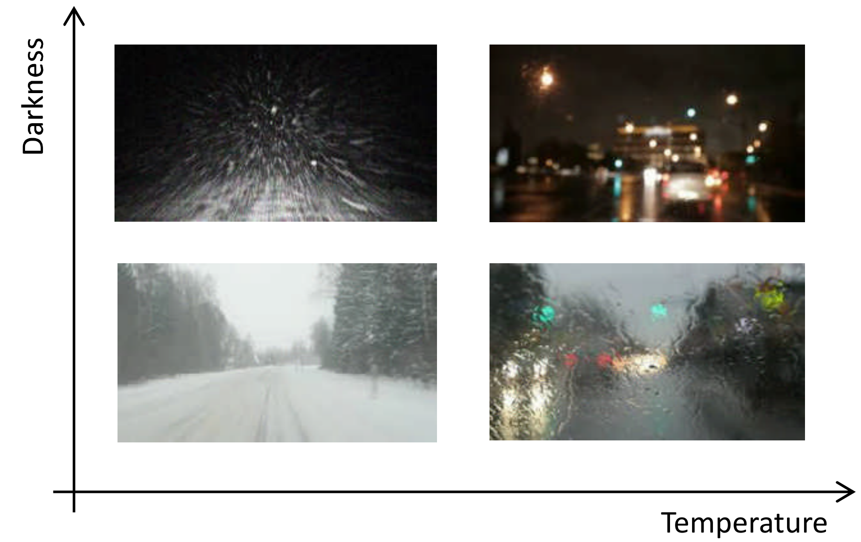
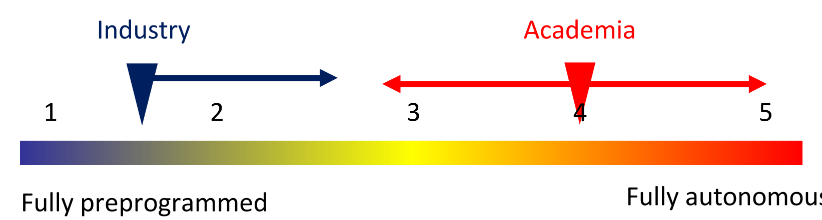


[Macadam, Understanding and Modeling the Human Driver, 2003]



All time, all weather, everywhere



My Objective in Today's Talk

Outline

History and state-of-the-art of autonomous driving

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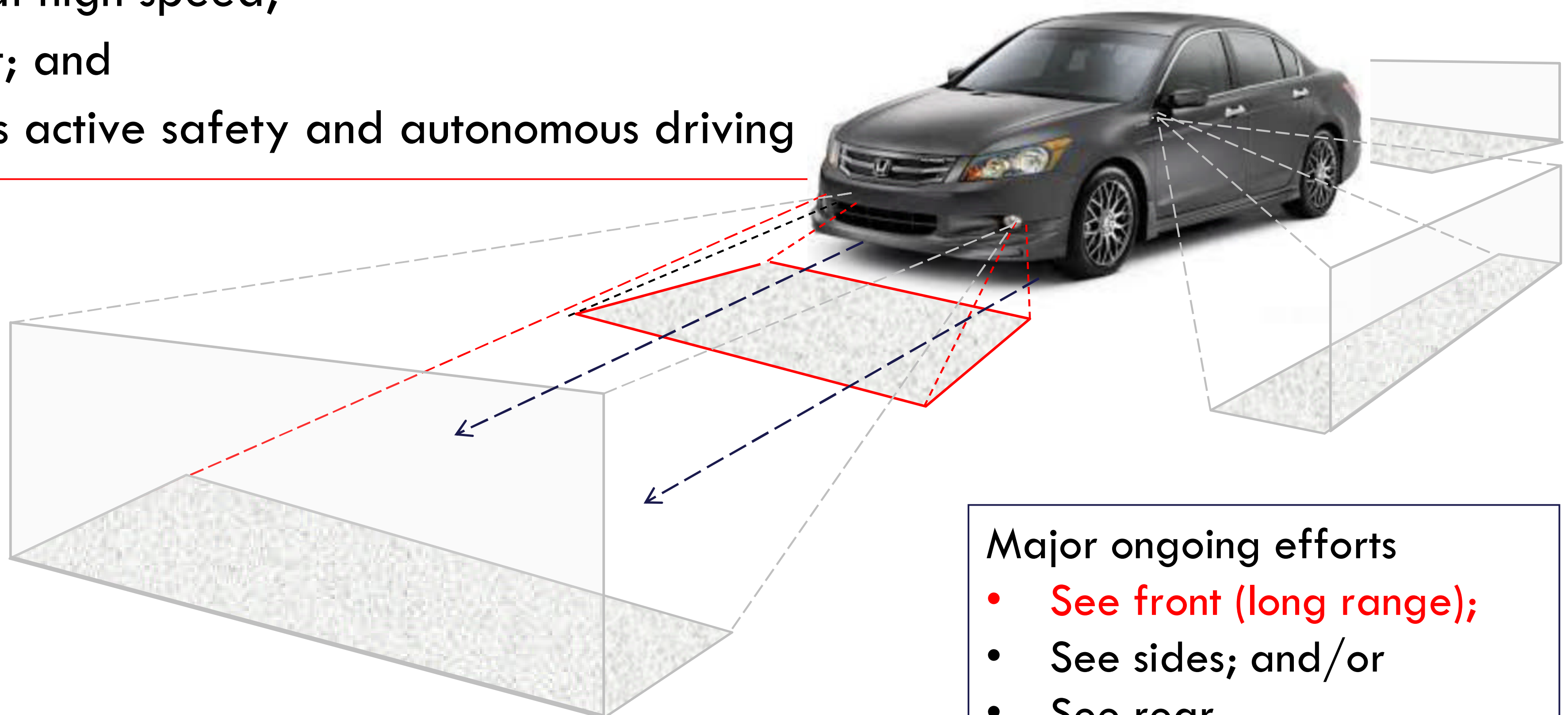
Develop a new technology that

- Could see ground (short range) using cameras;
- Works at high speed;
- Low cost; and
- Achieves active safety and autonomous driving



Major ongoing efforts

- See front (long range);
- See sides; and/or
- See rear.

Vehicle Safety vs. Road Condition

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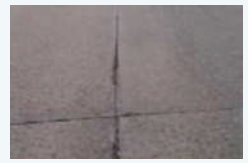
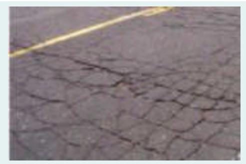
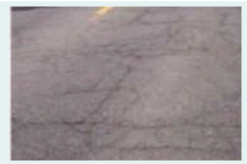
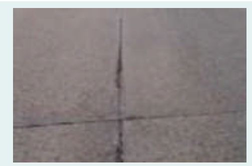
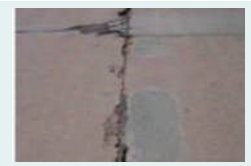
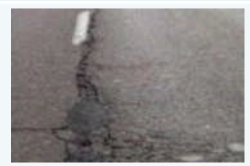
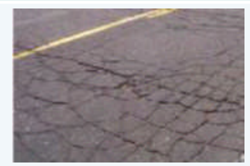
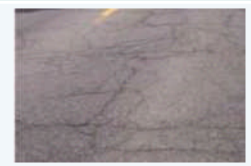
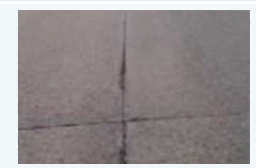
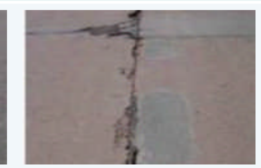
Danger/Severity Level	Immediate	Short-Term Future	Long-Term Future
None	 Unaffected pavement	 Unaffected pavement	Nothing is certain
Low	  Longitudinal, cross cracks, etc.	 Singular cracks	 Unaffected pavement
Medium	  Alligator, multiple cracks, etc.	  Cross cracks, spalling, etc.	 Singular cracks
High	  Potholes, surface deterioration, etc.	  Alligator, multiple cracks, etc.	  Cross cracks, spalling, etc.

Vechicle Safety vs. Road Type / Environmental Condition

Outline

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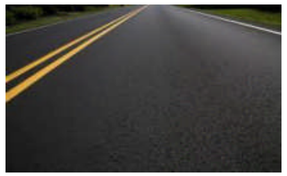
Gravel

Cobblestone



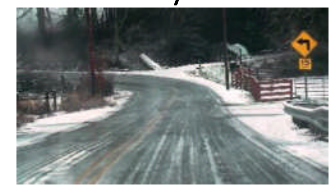
Asphalt

Concrete

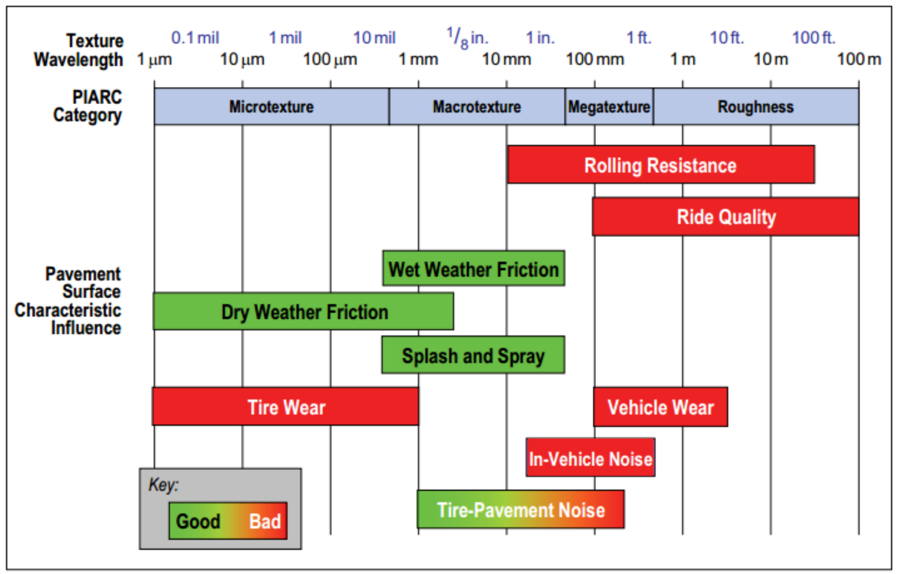
Rain

Heavy rain

Snow



Ice



World Road Association (PIARC) texture definitions

μ	Driving conditions	Braking distance at 50 km/t	Driving conditions and safety	Sprinkling procedure
< 0.1	wet ice or snow	not defined	impossible/ irresponsible	continuous sprinkling
0.1-0.15	winter conditions 0 C	66 m	very slippery, low safety	continuous sprinkling
0.15-0.25	winter conditions	39 m	slippery	sprinkling on hazardous places
0.30-0.40	intermediate conditions	33 m	satisfactory	no sprinkling
0.40-0.50	intermediate conditions	25 m	well satisfactory	---------" --------
0.50-0.60	summer conditions	16 m	very satisfactory	---------" --------
0.60-0.70	dry summer conditions	14 m	excellent	---------" --------

Friction increasing, absorptive agent and a method for its application to snow or ice covered surfaces, WO 2002057388 A1

Human Road Condition Monitoring

Outline

History and state-of-the-art of autonomous driving

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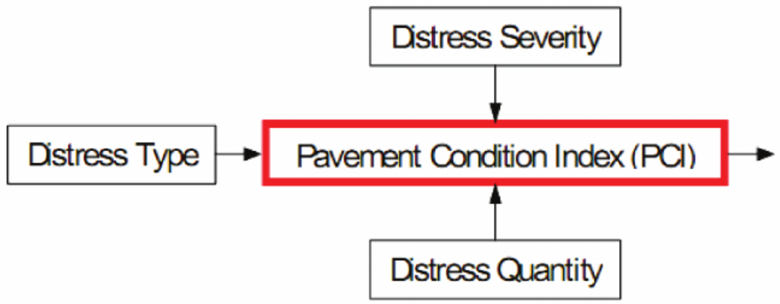
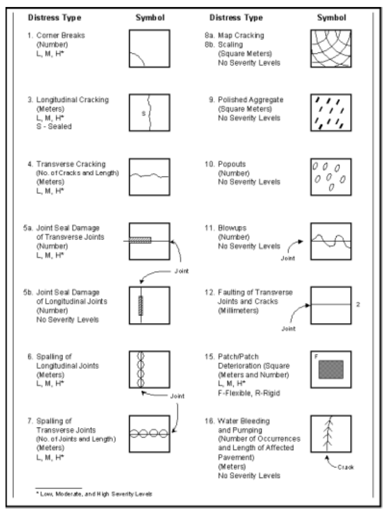
Autonomous driving using road surface measurement



							Severe	Very Severe	Few	Intermittent	Frequent	Extensive	Throughout
				stress (Si)					Density of Distress (Di)				
									<10	10-20	20-40	40-80	>80
							4	5	1	2	3	4	5
Surface Defects		Ravelling & loss of surface aggregate	3.0		x					x			
Surface Defects		Flushing	1.5		x					x			
Surface Deformations		Rippling and Shoving	1.0	x					x				
Surface Deformations		Wheel Track Rutting	3.0	x					x				
Surface Deformations		Distortion	3.0		x					x			
Cracking	Longitudinal Wheel Track	Single and Multiple	1.5	x					x				
Cracking	Longitudinal Wheel Track	Alligator	3.0	x					x				
Cracking	Centerline	Single and Multiple	0.5			x					x		
Cracking	Centerline	Alligator	2.0	x					x				
Cracking	Pavement Edge	Single and Multiple	0.5			x					x		
Cracking	Pavement Edge	Alligator	1.5			x					x		
Cracking	Transverse	Half, full and multiple	1.0	x					x				
Cracking	Transverse	Alligator	3.0	x									
Cracking	Longitudinal – meander or mid-lane		1.0										
Cracking	Random		0.5										



PCI Decision Matrix

TIME OF IMPROVEMENT	FREEWAY	ARTERIAL	COLLECTOR	LOCAL
Adequate	>85	>85	>80	>80
6 to 10 years	76 to 85	76 to 85	71 to 80	66 to 80
1 to 5 years	66 to 75	56 to 75	51 to 70	46 to 65
NOW Rehabilitate	60 to 65	50 to 55	45 to 50	40 to 45
NOW Reconstruct	<60	<50	<45	<40

Human decision-making
- Factors of success:
  - Detection capability
  - Experience
- Sensing: Visual
- Decision making:
  - Knowledge (Physics) driven
  - Data driven

Human → Automatic

Project sponsored by

[redacted]

Design Constraints for Road Condition Modeling

Outline

History and state-of-the-art of autonomous driving

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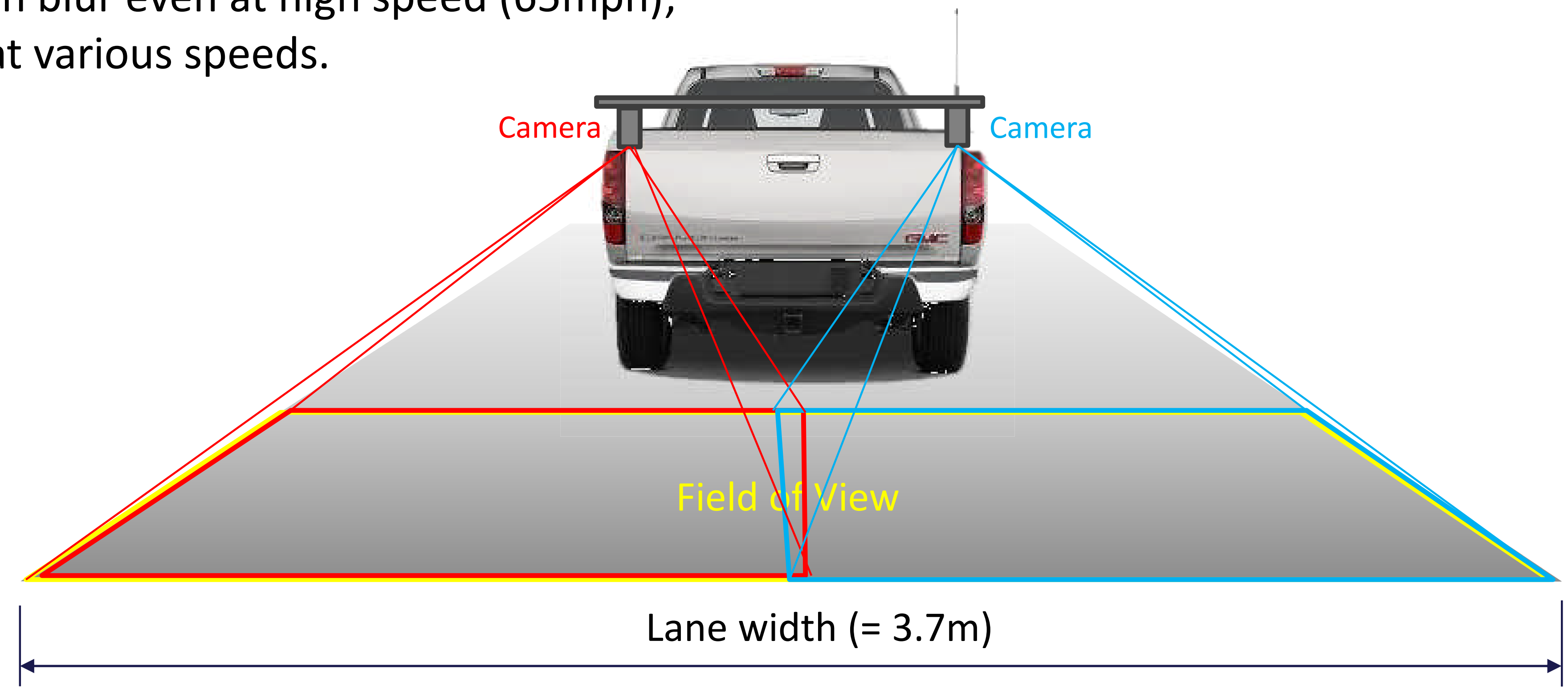
Autonomous driving using road surface measurement

Consortium for Tire-road Analysis Technology
ConsTAnT

Primary design constraints

- Scan lane width (= 3.7m);
- Use cameras;
- No motion blur even at high speed (65mph);
- Imaging at various speeds.



Frame Rate for Road Condition Monitoring

Outline

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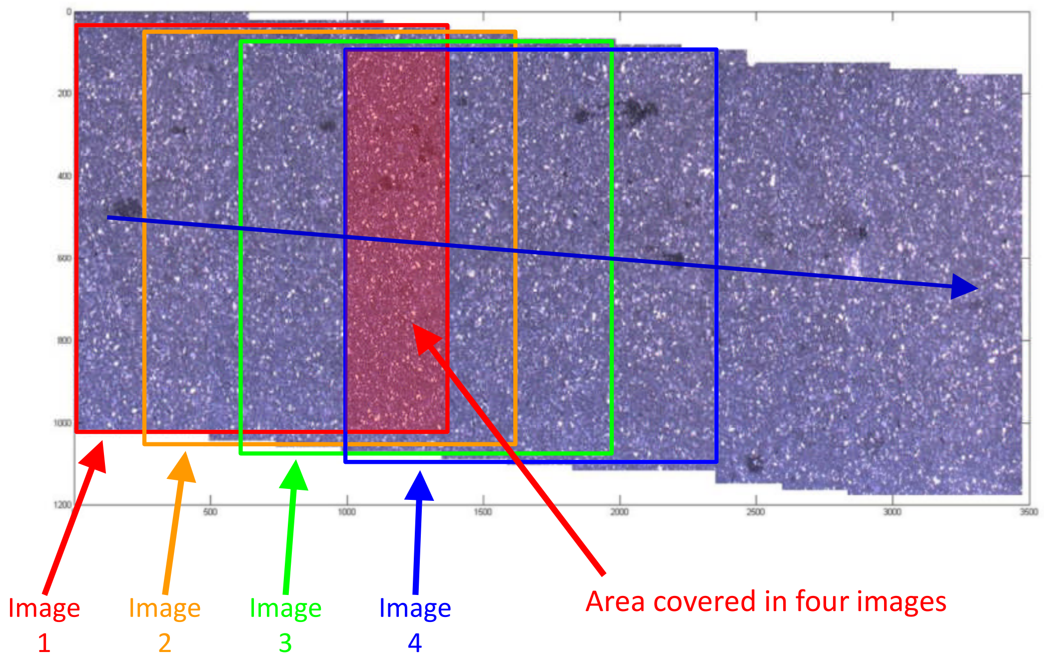
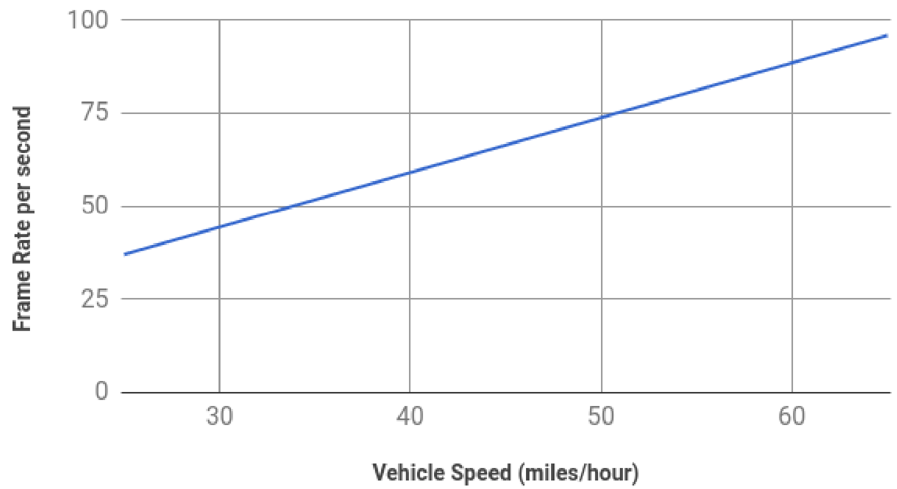


Road map stitched by 10 consecutive images

Frame rate

- One feature covered by 4 images for road profiling with increased accuracy at different speeds.

Varying frame rate



Imaging Covering Feature in 4 Images with No Motion Blur

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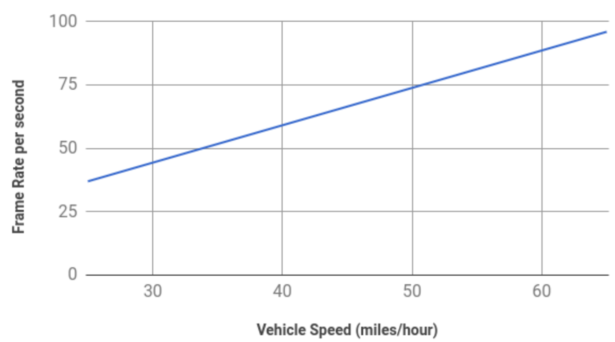
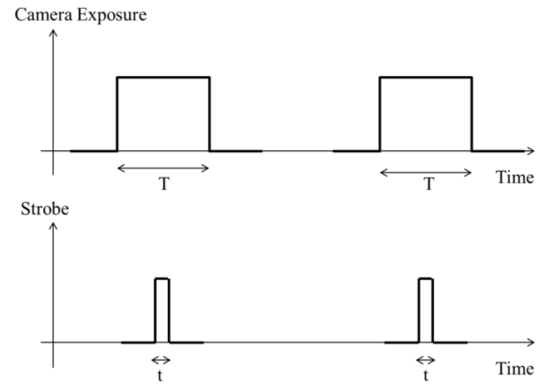
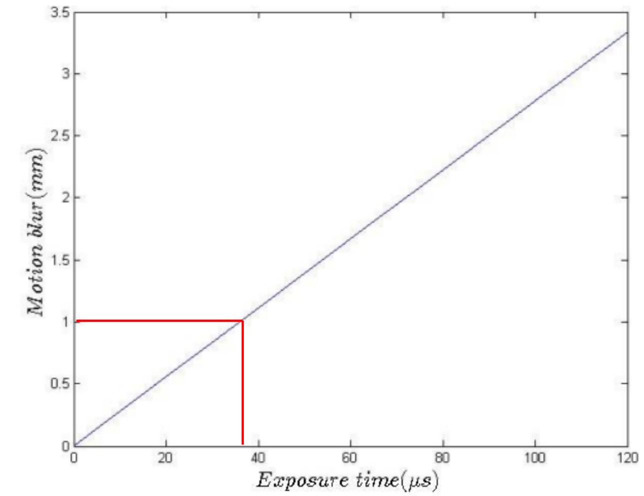


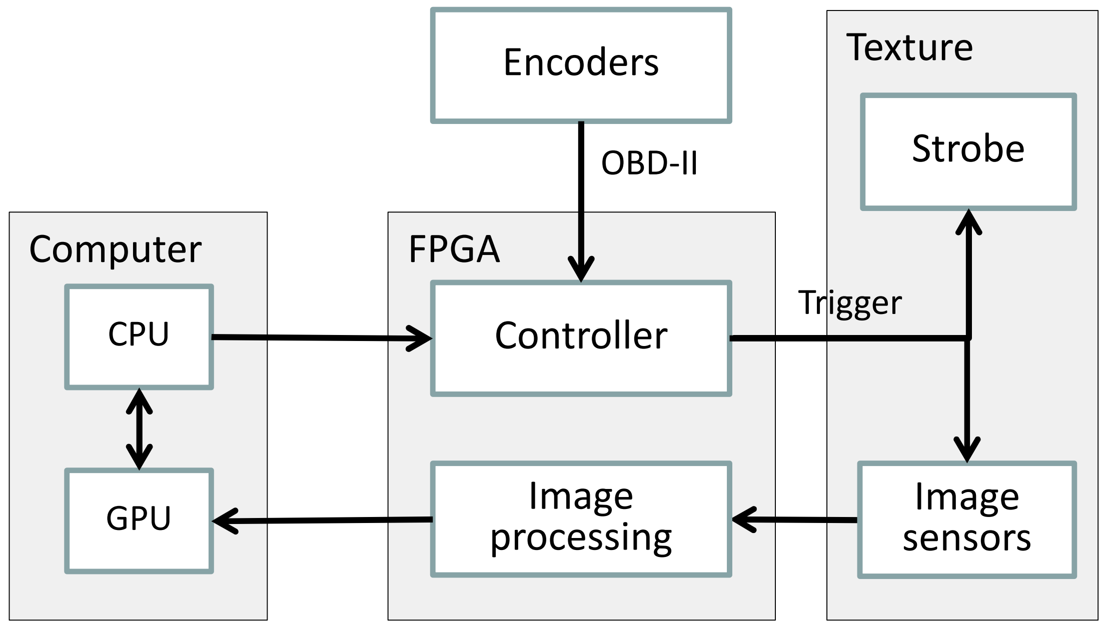
Frame rate vs. speed



Imaging with no motion blur using strobe

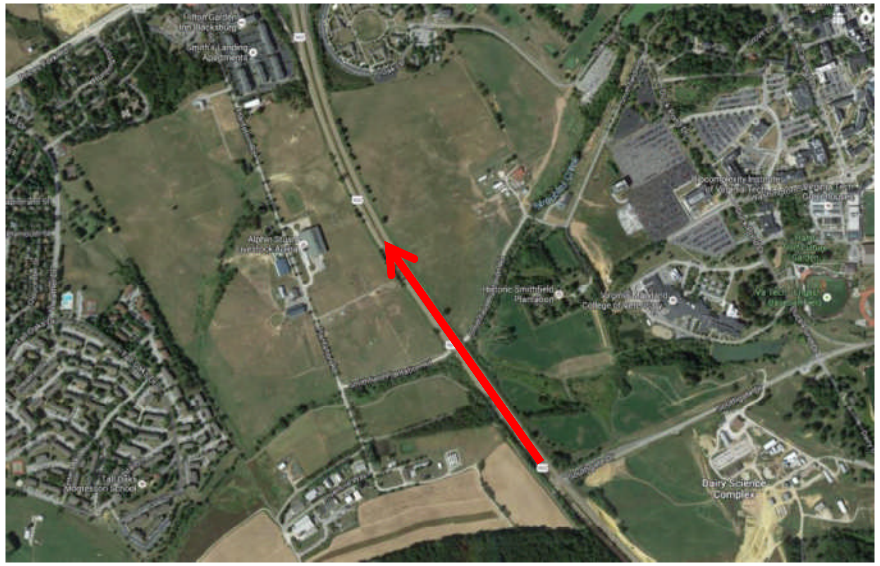


Shutter speed vs. motion blur



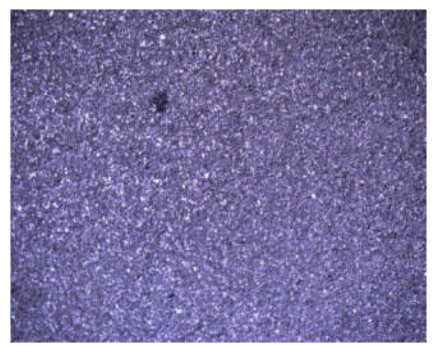
FPGA-based system

High Speed Experiment



- **Test road position:** US-460 highway near Blacksburg
- **Vehicle speed:** 60 to 65 miles/hour (97 to 105 km/h)
- **Camera shutter speed:** 0.04ms
- **Frame rate:** 150fps

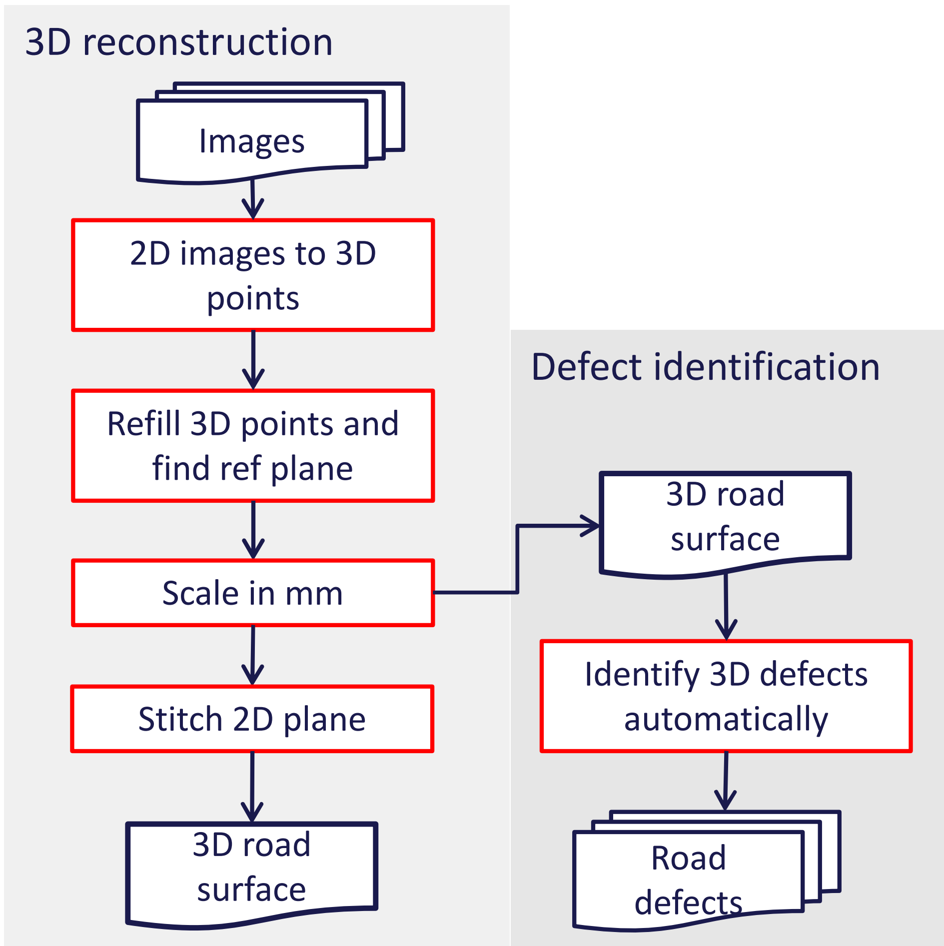
No motion blur



High-Precision 3D Reconstruction

Outline

Proposed overall framework: 5 steps



Each process

- **2D images to 3D points**: Represent 3D point cloud <u>without unit</u>
- **Refill 3D points and find ref plane**: Guarantee <u>resolution</u> of measurement and measure <u>in mm</u>
- **Stich 2D plane**: Create long road
- **Identify 3D defects**: Identify road defects

Field Tests - Accuracy

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Pothole (depth~10mm)

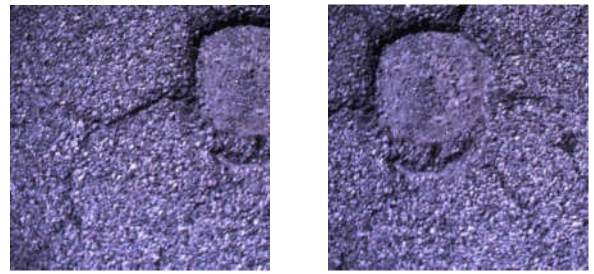
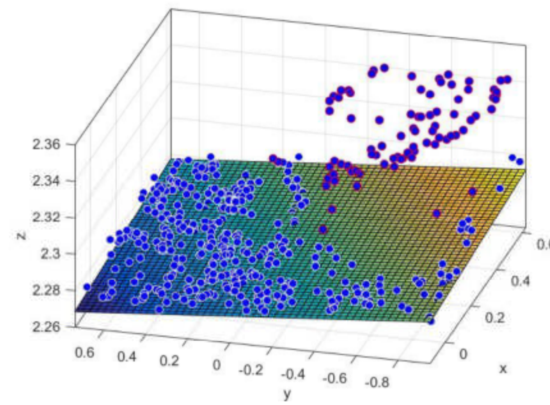


Image 1 Image 2

Two consecutive images



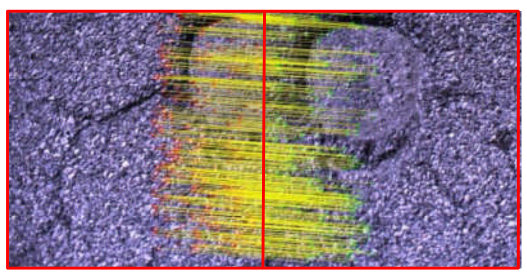
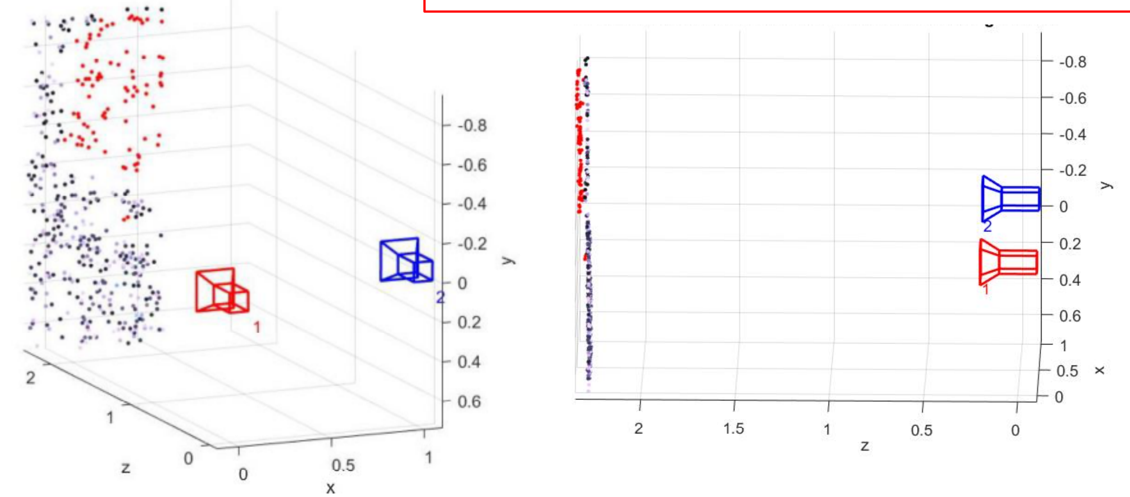


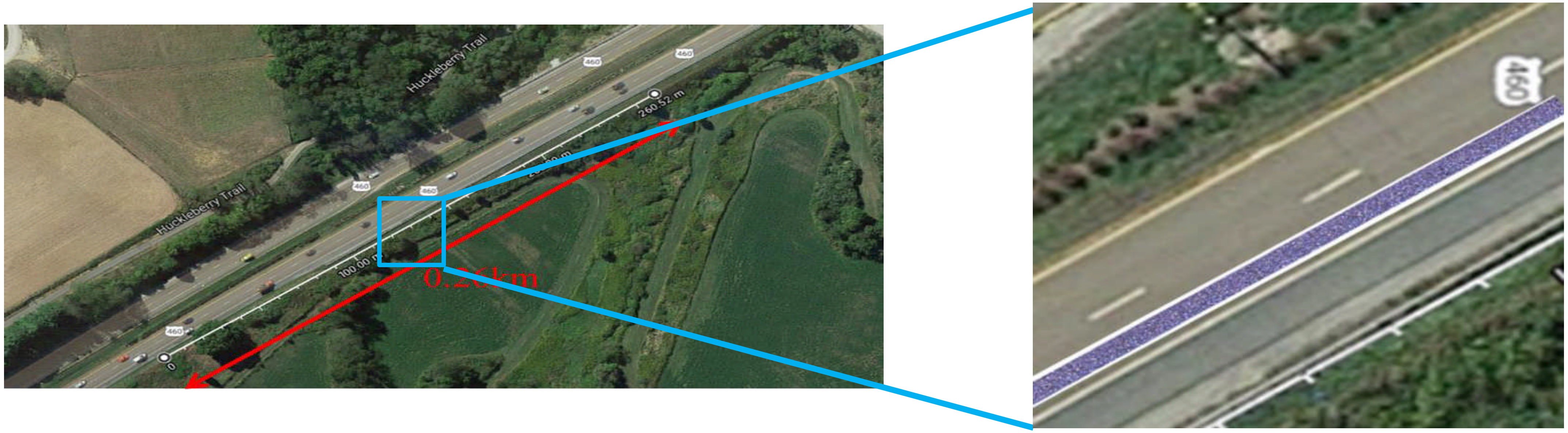
Image 1 Image 2

Feature matching

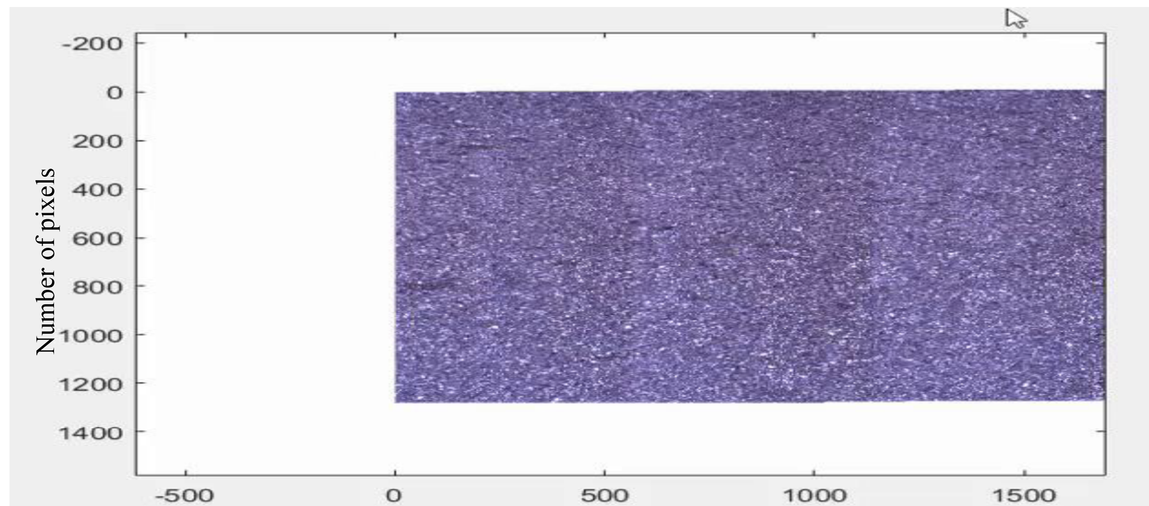
Describing pothole three-dimensionally



Road Image Stitching for 900 Images



- Road map registering to Google Map
- Clear continuous road surface visualization when zooming in



Finest 3D Google Map! (mm resolution)

3D Reconstruction for 120m Road

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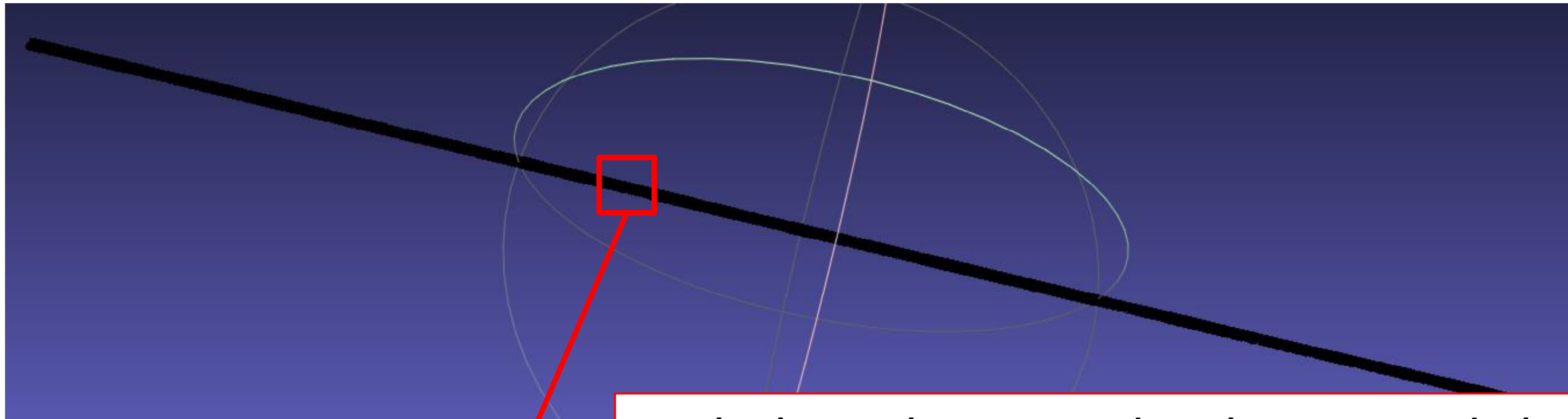
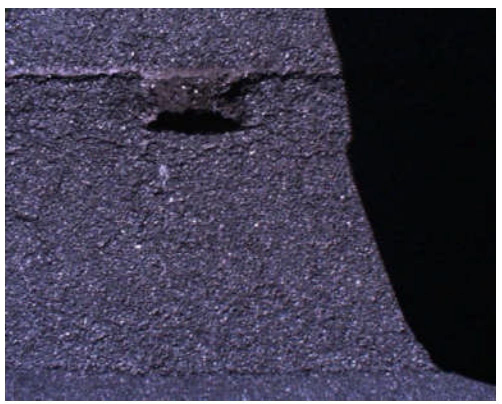
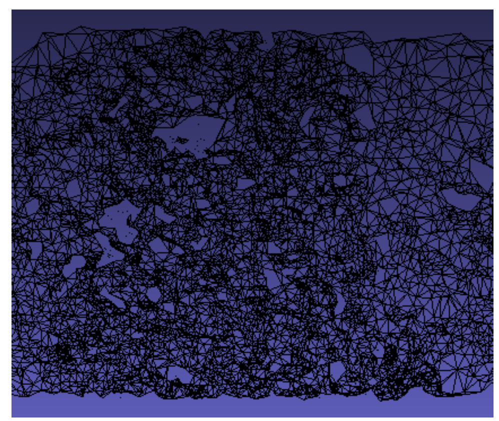
3D reconstruction for 120m road



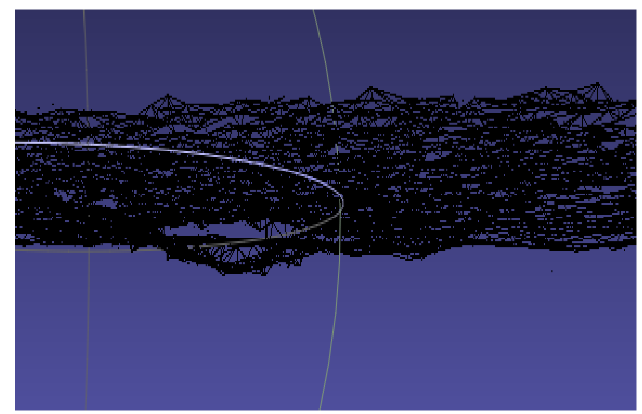
Pothole with 10mm depth captured clearly



Original image



Mesh top view



Mesh front view

Automatic Pothole Detection

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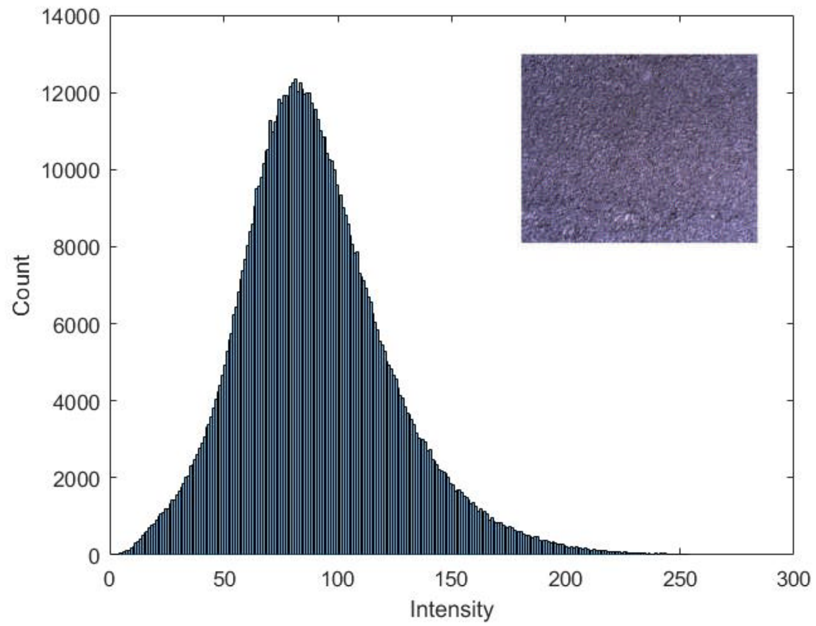
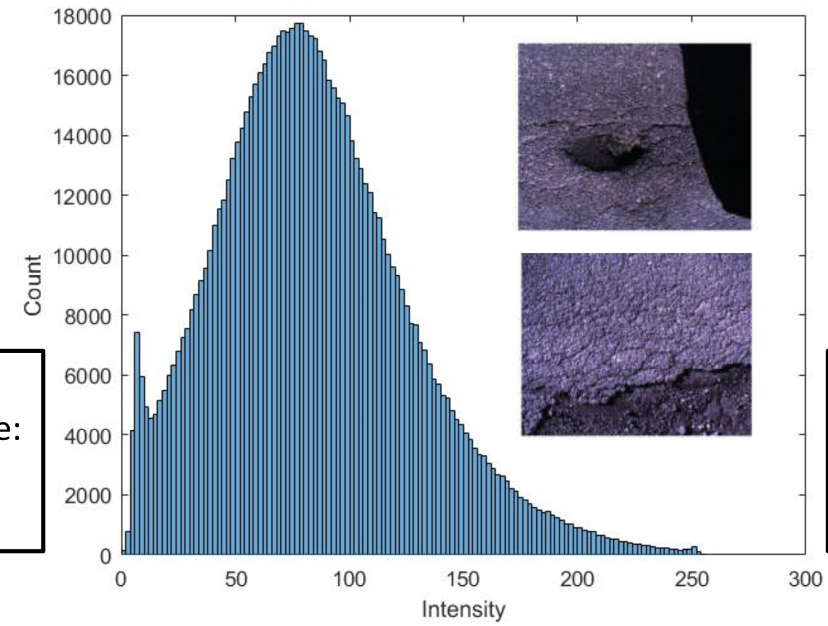
Image without the pothole

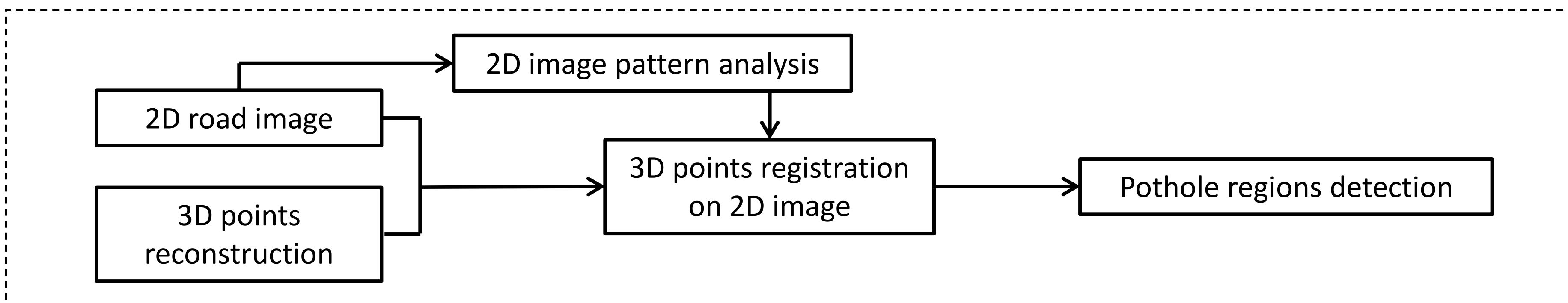


Statistics of intensity value: Flat surface pattern

Images with the pothole



Statistics of intensity value: Pothole pattern



Field Tests – Detection of Various Potholes

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

SfM based road surface measurement

Defect identification

Autonomous driving using road surface measurement

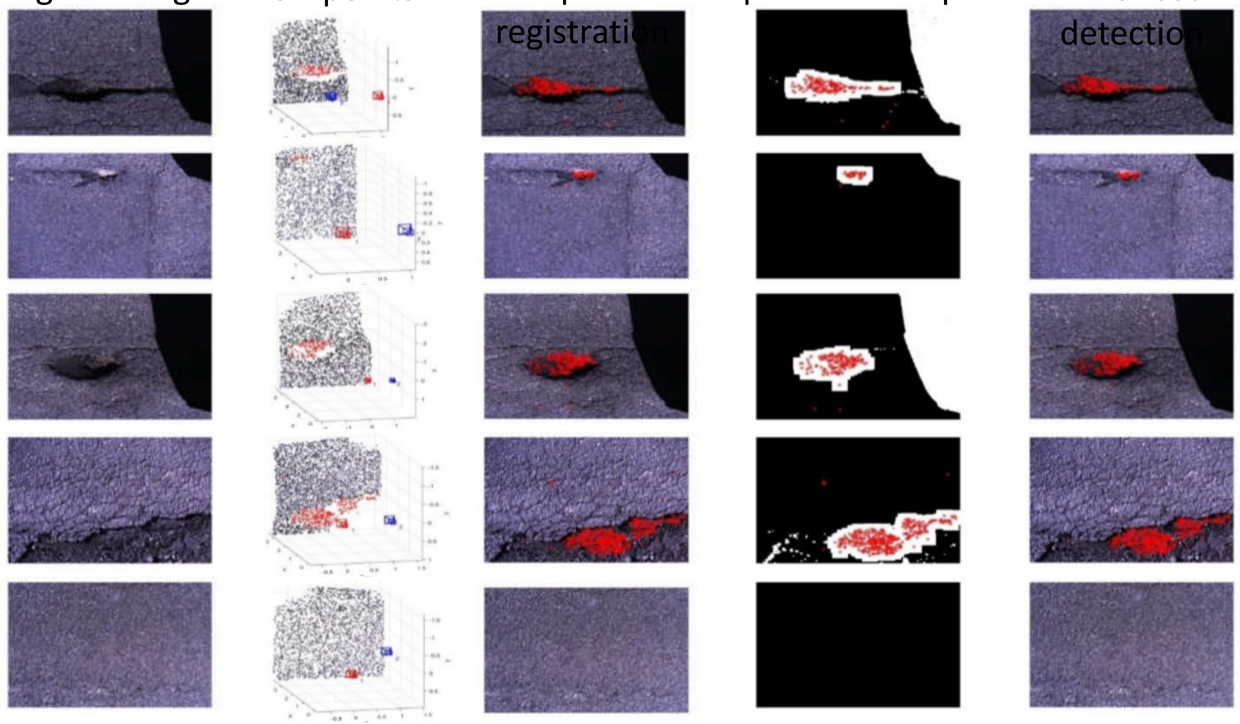
Parameters

Parameter	Value
Speed	100 km/h
Number of images	3,500
Pothole depth threshold	10 mm

Results

		Detected	
		Pothole (positive)	No Pothole (negative)
Measured	Pothole (positive)	301 (8.6%)	7 (0.2%)
	No Pothole (negative)	168 (4.8%)	3024 (86.4%)

Original images | 3D points | 3D points registration | 2D pattern + 3D points | Enhanced detection



- 95% positive due to well-maintained road condition.
- False negative due to low threshold.
- False positive due to shadow and marks.

Bayesian Approach for Stochastic 2D Defects

Outline

History and state-of-the-art of autonomous driving

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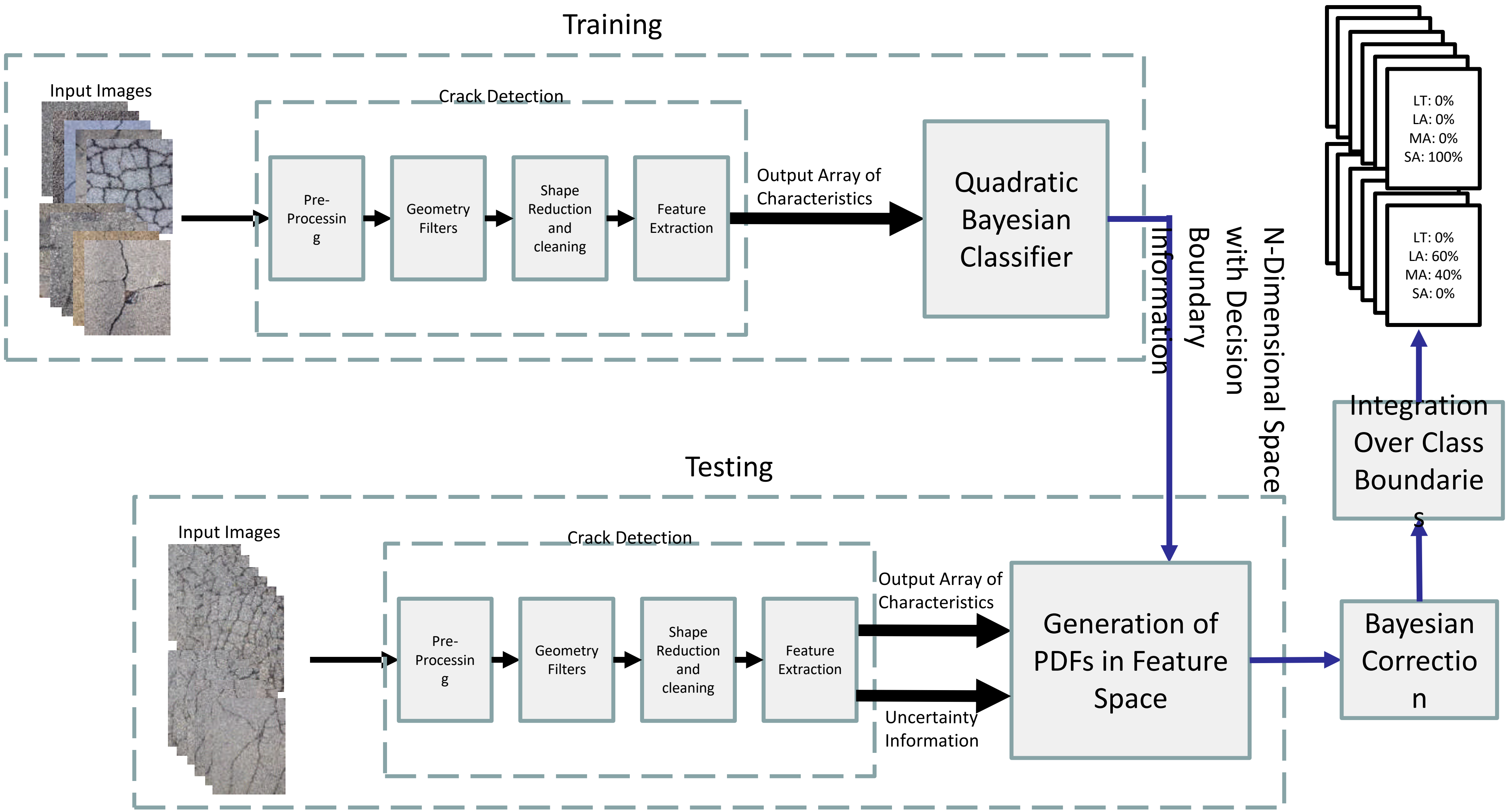


Field Tests: Detection of Various Cracks

Outline

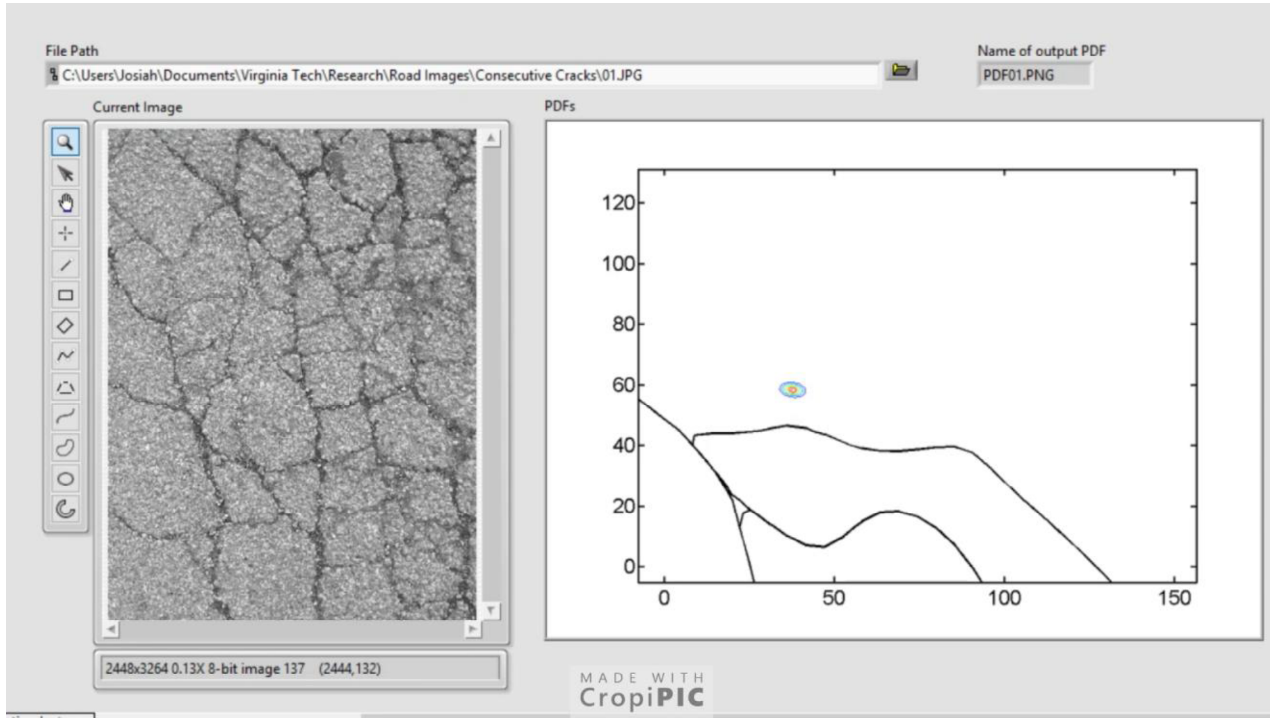
History and state-of-the-art of autonomous driving

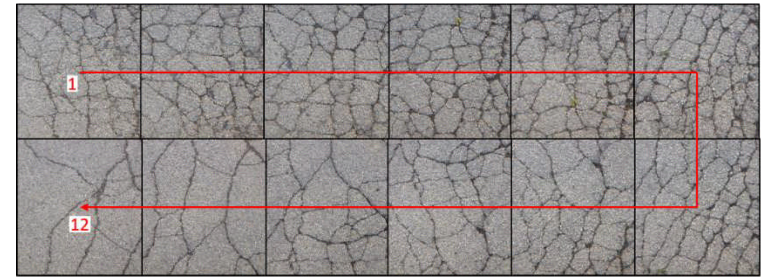
Road surface measurement for autonomous driving

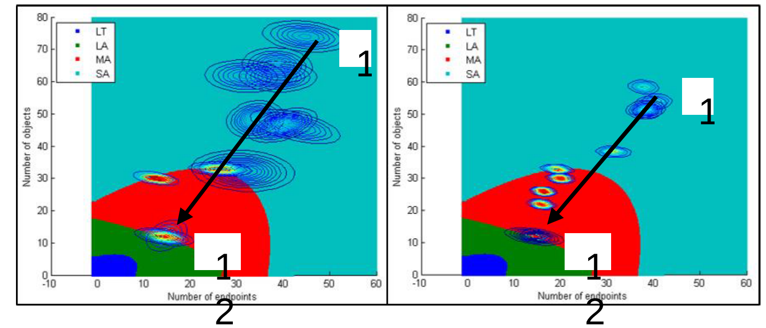
SfM based road surface measurement

Defect identification

Autonomous driving using road surface measurement







Results

		Detected	
		Crack (positive)	No crack (negative)
Measured	Crack (positive)	525 (16.4%)	1572 (49.2%)
	No crack (negative)	352 (11.0%)	743 (23.2%)

- False negative due to low threshold.
- False positive due to shadow and marks.

Current Autonomous Driving Efforts

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

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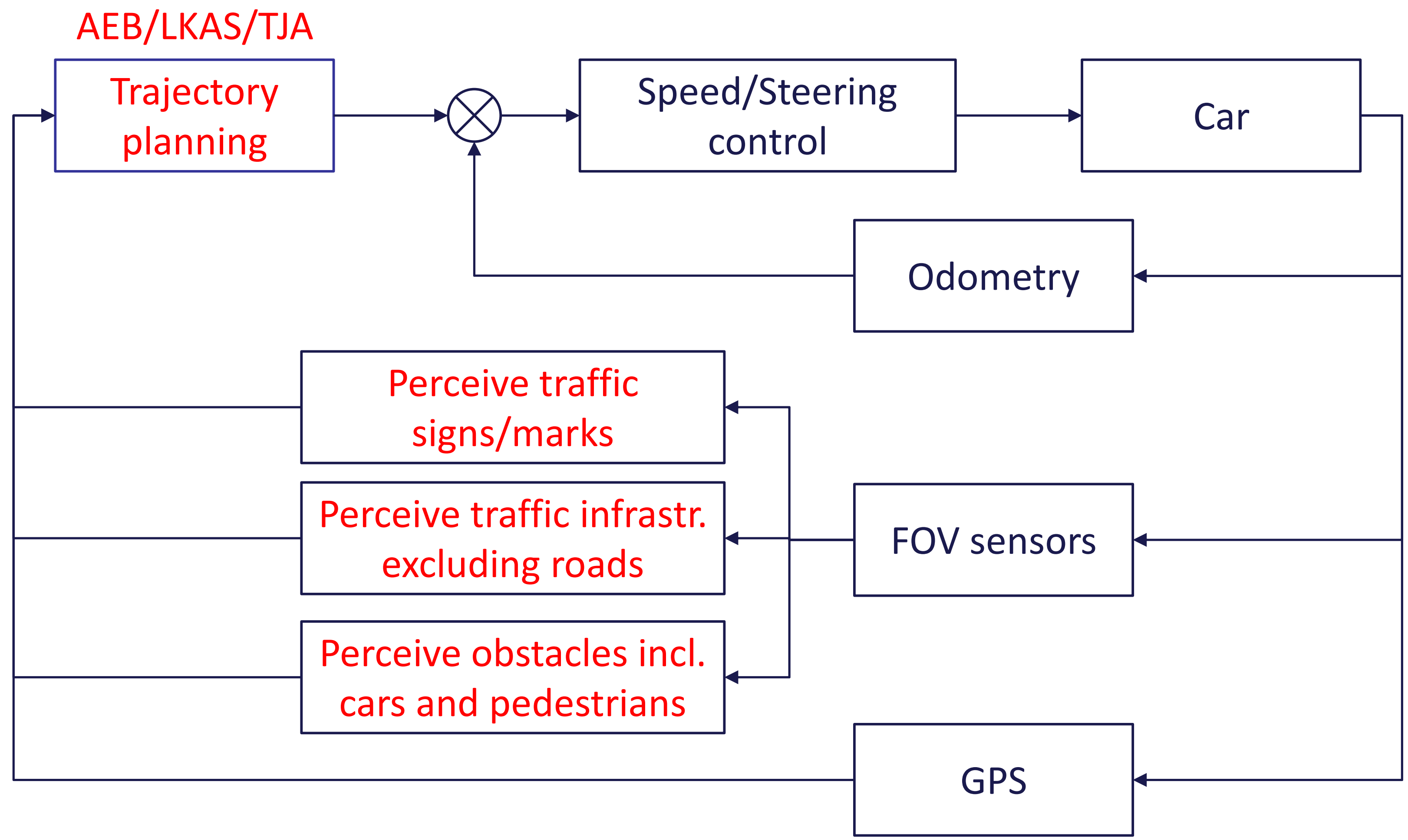
Autonomous driving using road surface measurement



Proposed Autonomous Driving: See Ground

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

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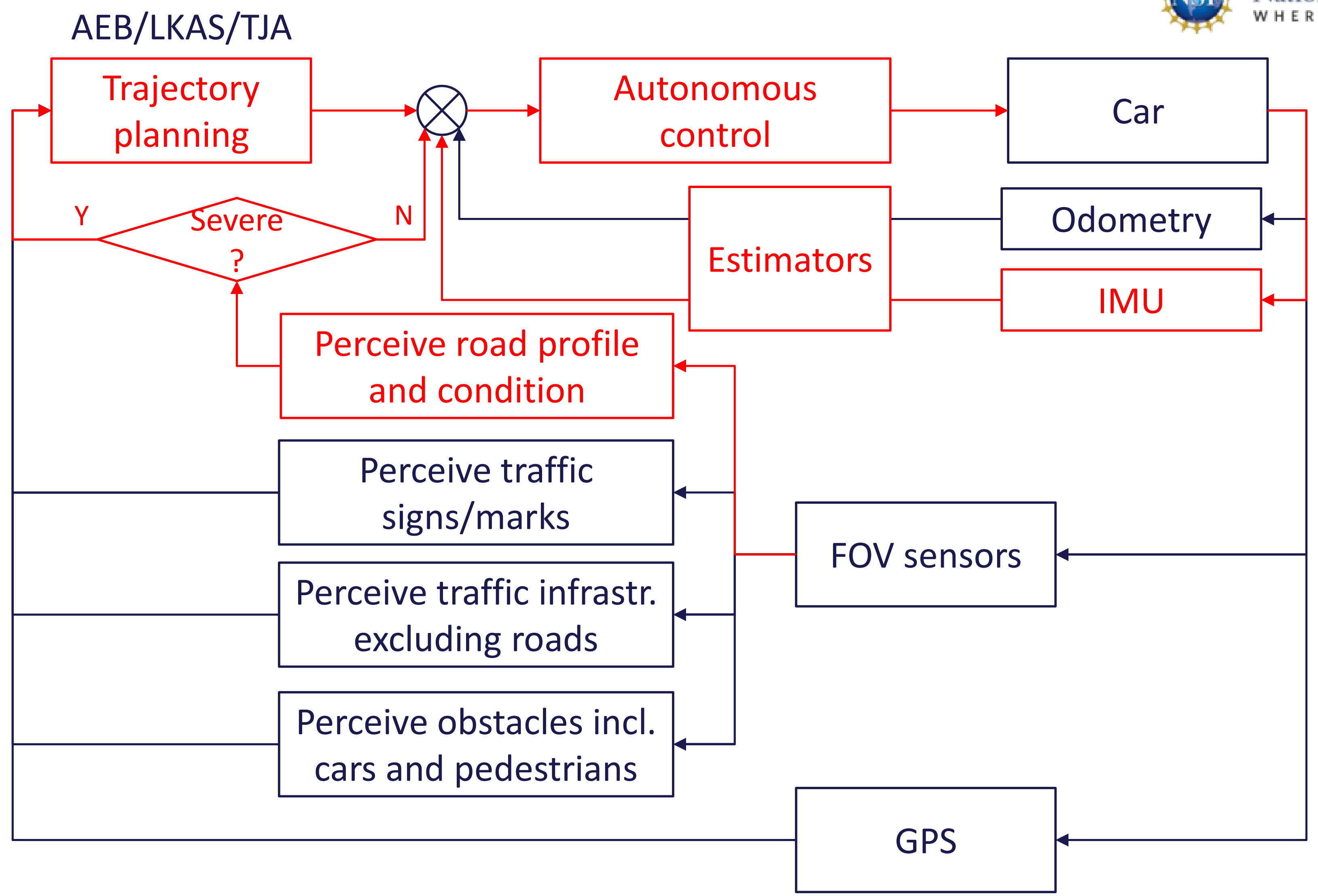
Defect identification

Autonomous driving using road surface measurement



Field Test Arrangement

Outline

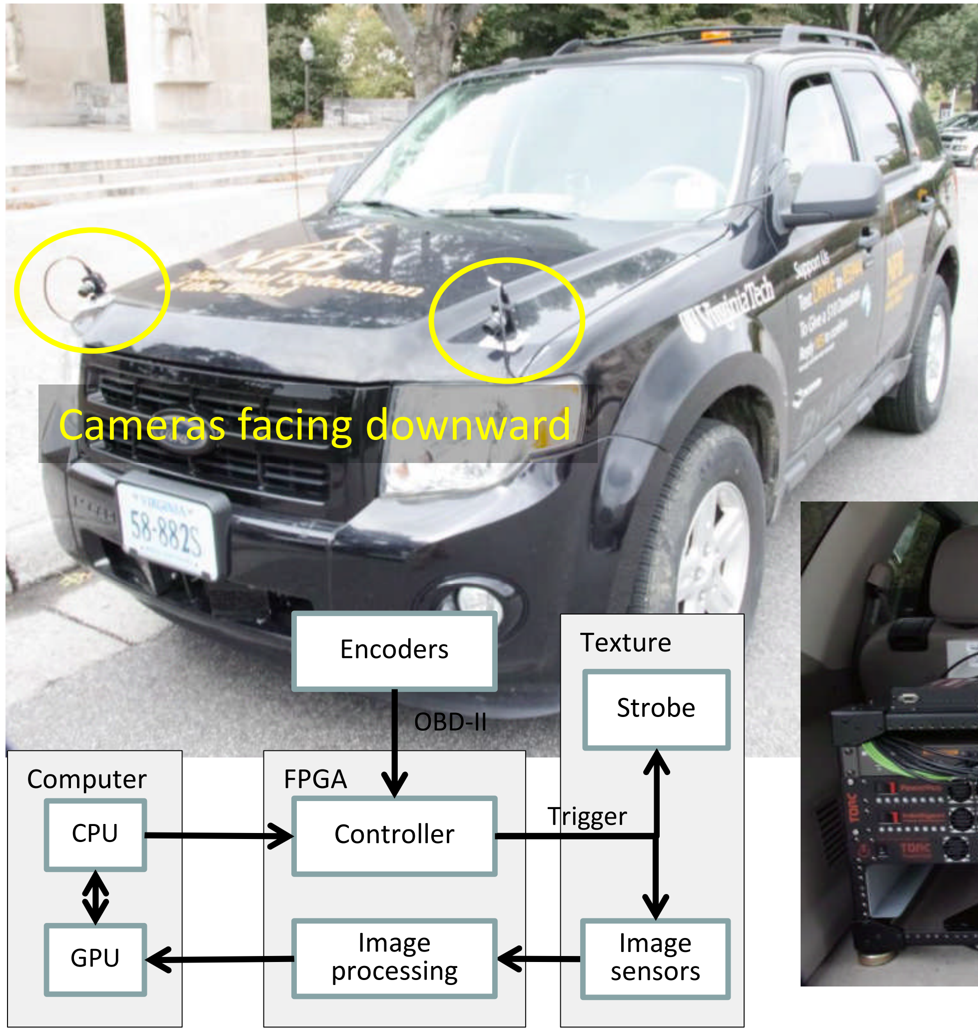
History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

SfM based road surface measurement

Defect identification

Autonomous driving using road surface measurement



Test vehicle

Public roads in Blacksburg

Road Condition and Naturalistic Driving

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

SfM based road surface measurement

Defect identification

Autonomous driving using road surface measurement

Uncritical road condition (< 2-3cm)
- Ignore and bounce

Critical road condition (> 2-3cm)
- Slow down (< 5cm)
- Steer and avoid (> 5cm)

Real-time Perception of Road Profile and Condition

Outline

History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

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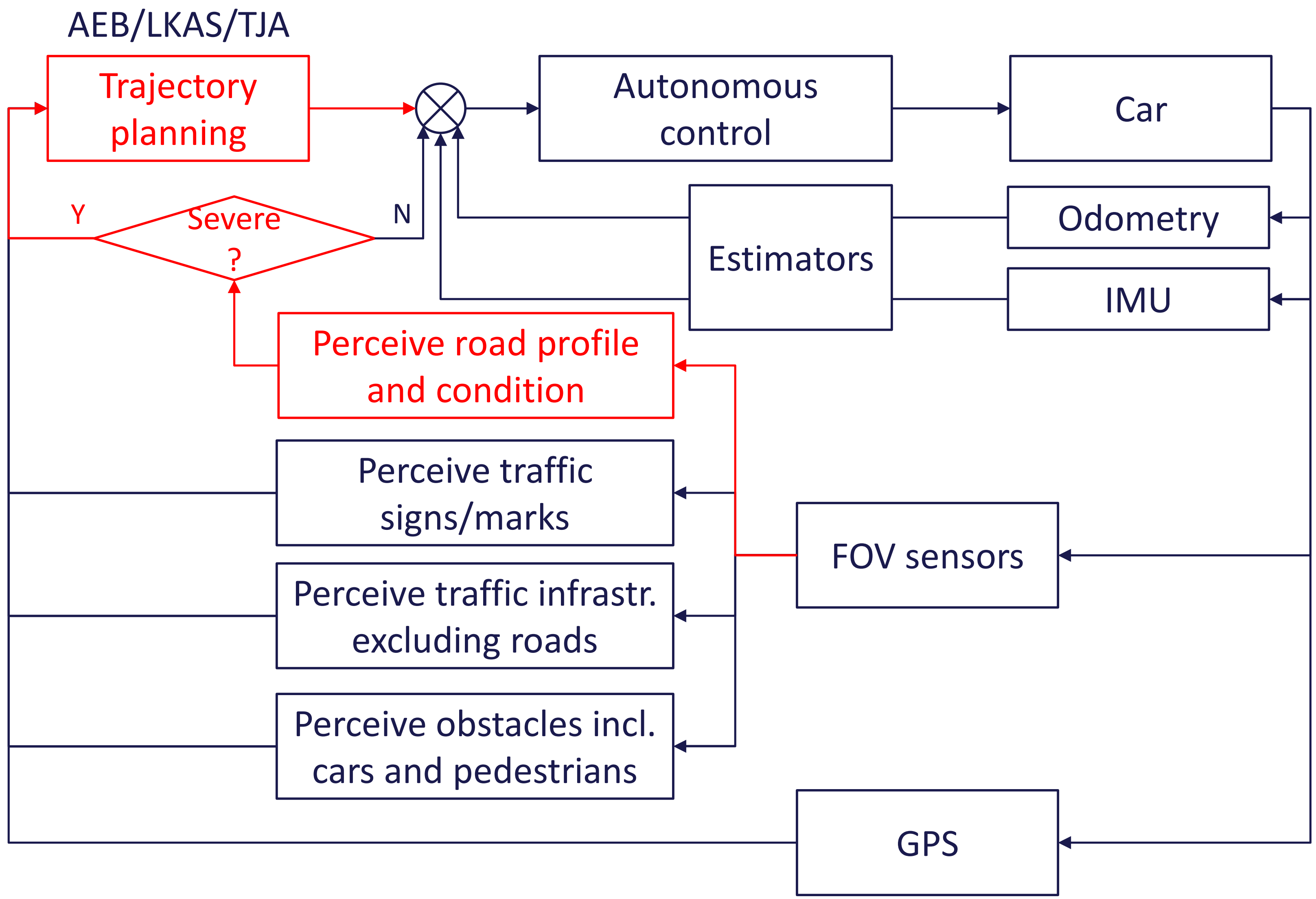
Autonomous driving using road surface measurement



Real-time 3D Road Profiling

Outline

History and state-of-the-art of autonomous driving

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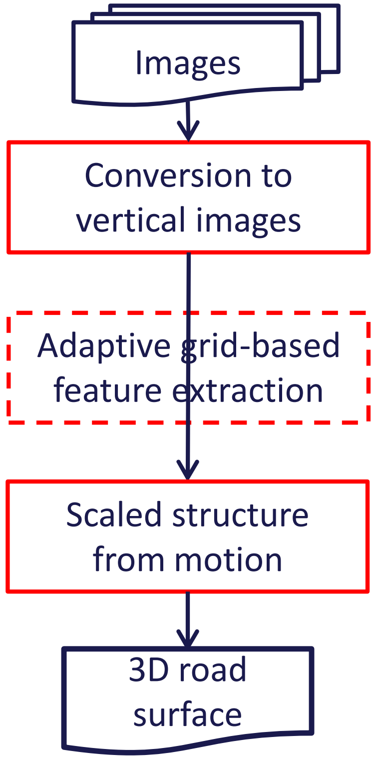


Autonomous Emergency Stop into Curb

Outline

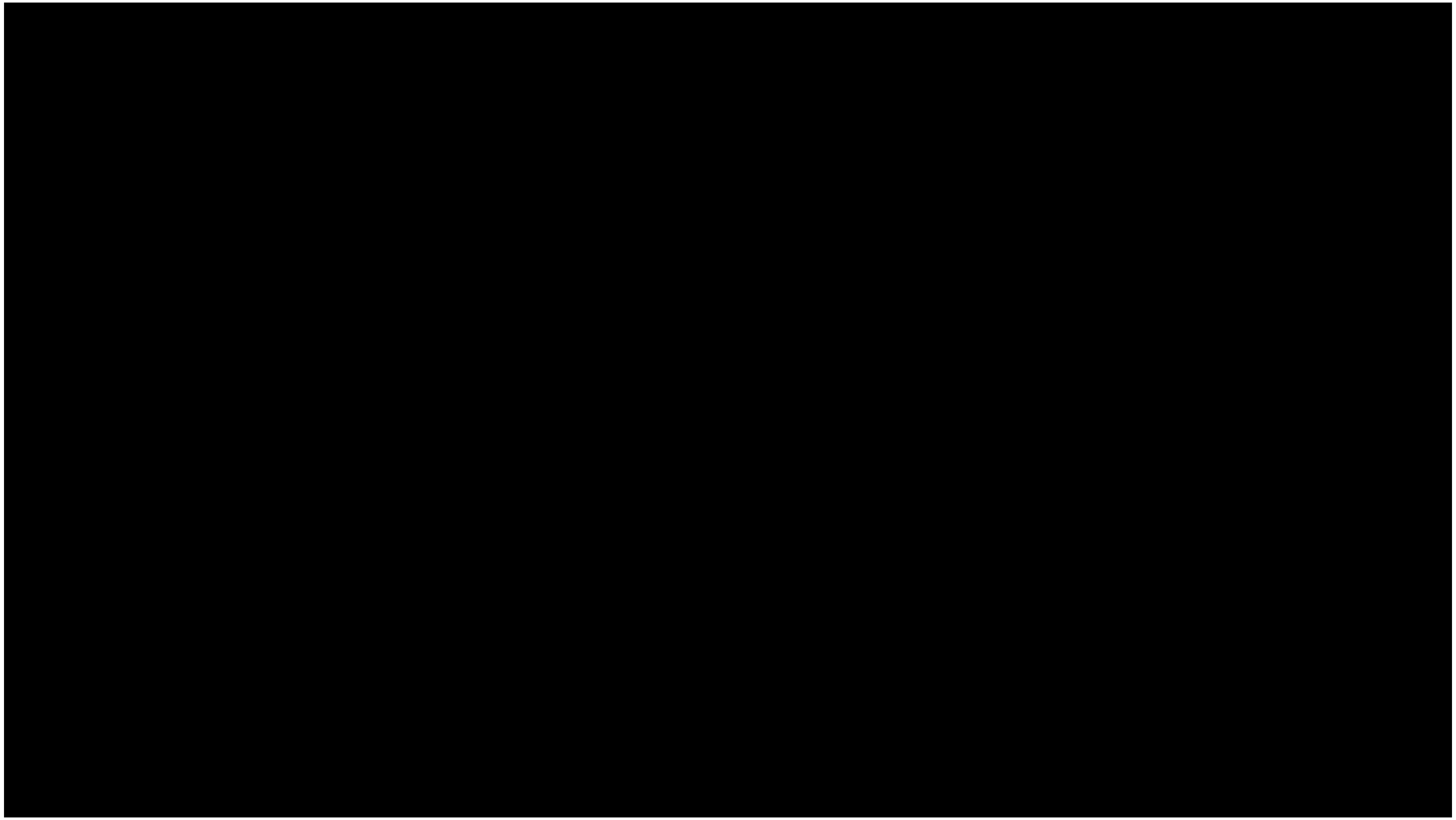
History and state-of-the-art of autonomous driving

Road surface measurement for autonomous driving

SfM based road surface measurement

Defect identification

Autonomous driving using road surface measurement



Thank You!

Proposed technologies

- Road surface measurement
- Autonomous defect identification
- Autonomous driving

Team VICTOR

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