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Autonomous Driving

from Research to Deployment

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Content

- Autonomous driving architecture
- Sensors and hardware
- Robotic Operating System (ROS)
- How to achieve maximum robustness?
  - Simulation and synthetic data
  - Closed loop automation
  - Auto-labeling
- Autonomous driving commercialization
- Kuartis technology stack

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Company

- est. @ April 2012
- ODTÜ-Teknokent
- 50 People
- CS(24) and EE (26)
- 4 PhD + 3 PhDc
- 7 MSc + 5 Candidate

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ADAS and AV/AD Market

1. "The global semi-autonomous vehicle market demand is anticipated to reach 60.1 million units by 2028“
2. "The global ADAS market size is projected to grow from USD 27.2 billion in 2021 to USD 74.9 billion by 2030, at a CAGR of 11.9%"
3. "Self-driving car market size was estimated at USD 56.21 Billion in 2021 and is expected at a CAGR of 36.47% to USD 220.44 Billion USD by 2026."

1. https://www.bloomberg.com/press-releases/2021-07-21/semi-autonomous-vehicle-market-demand-to-reach-60-1-million-units-by-2028-grand-view-research-inc
2. https://finance.yahoo.com/news/global-adas-market-size-projected-100700754.html
3. https://www.marketdataforecast.com/market-reports/self-driving-cars-market

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Self Driving Car Companies

- Waymo
- Zoox, Cruise, Argo, Aurora, Motional (Nutonomy)
- TuSimple, Kodiak Robotics,
- Momenta, WeRide, Baidu, Pony AI,
- Easy mile

- Tesla
- Toyota, Mercedes etc.

ADAS/AV Use Cases

- L1/L2/L3 ADAS
- Robotaxis, robo-shuttles
- Autonomous mining
- Autonomous port operations
- Autonomous material handling / tractor / haulage
- Last mile delivery
- Defense: Unmanned (armed / unarmed) Ground Vehicles
  - Surveillance / border security
  - Logistics / convoy
  - Combat support

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ADAS/AV Use Cases - Defense

Source: https://www.youtube.com/watch?time_continue=61&v=daFeqDD69uw&feature=emb_logo

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Autonomous Driving Workflow

SENSE ⇢ SOLVE ⇢ GO!

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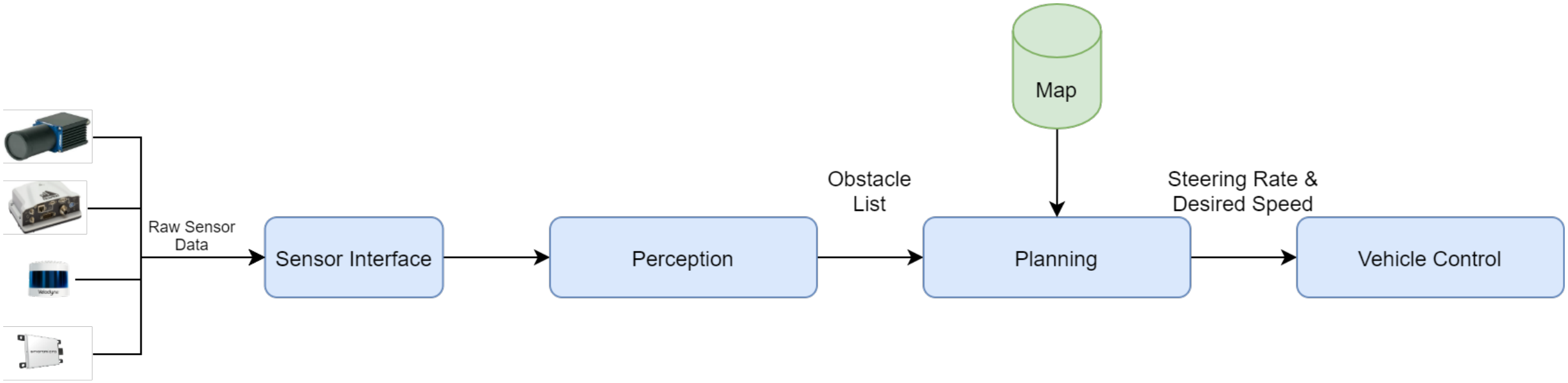
Autonomous Driving Workflow



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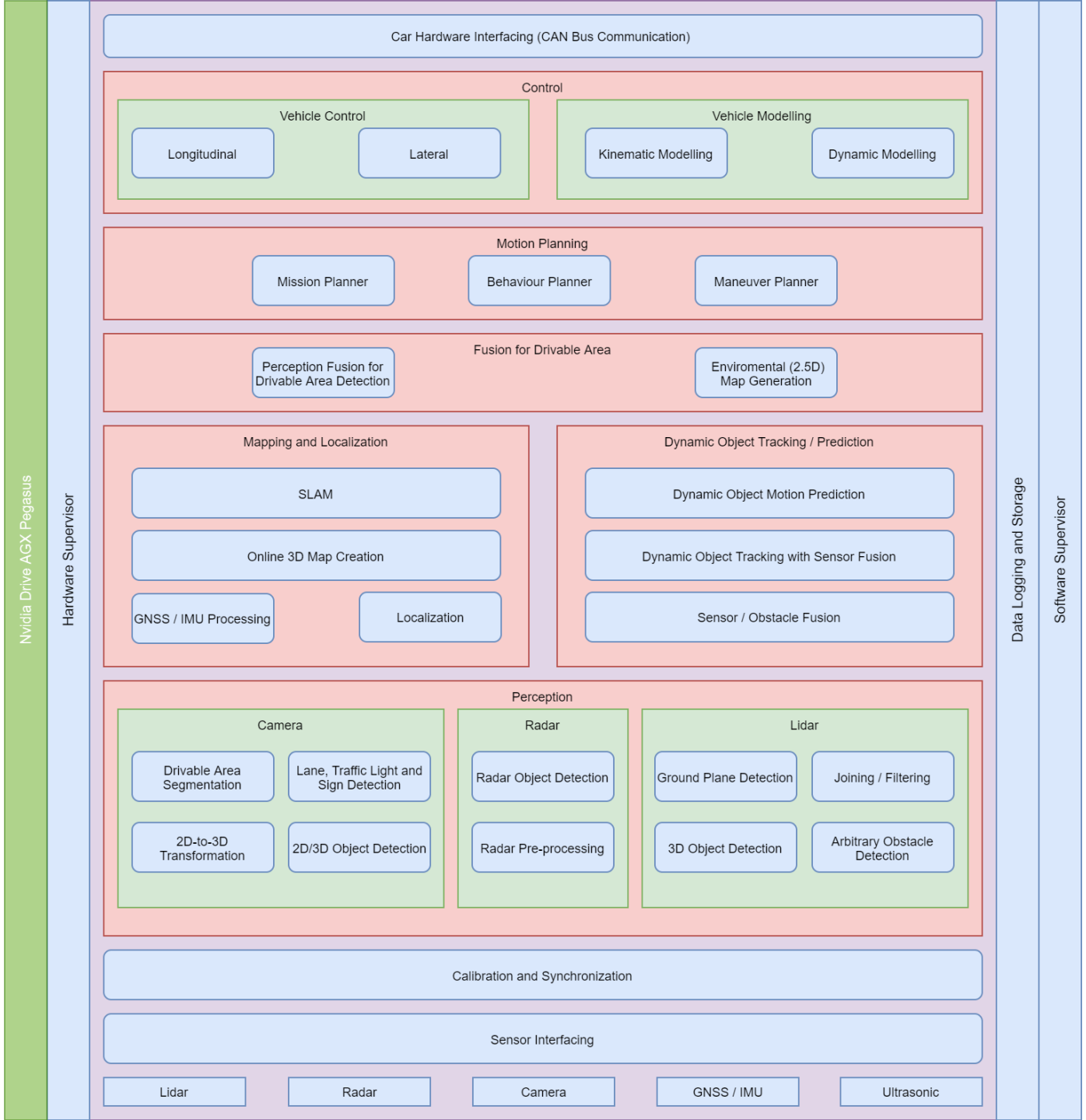
Architecture



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Sensor Fusion & Redundancy

	Camera	LIDAR	Radar	Sensor Fusion
Light	★	★★★	★★★	
Noise	★★★	★★	★	
Resolution	★★★	★★	★	
Weather	★	★★	★★★	★★★
Velocity	★	★★	★★★	
Abs. Distance	★	★★★	★★★	
Class. Power	★★★	★★★	★★	
Cost	★★★	★	★★	

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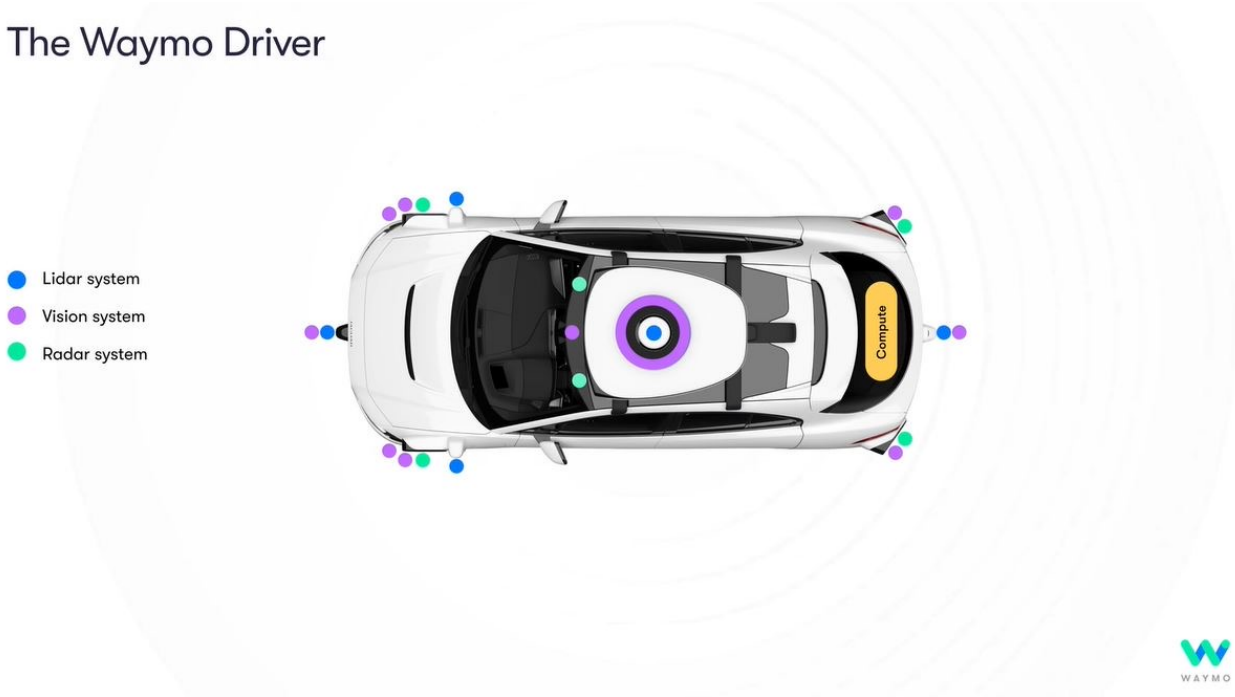
Sensor Suite (Waymo 5th gen)



https://blog.waymo.com/2020/03/designing-5th-generation-waymo-driver.html

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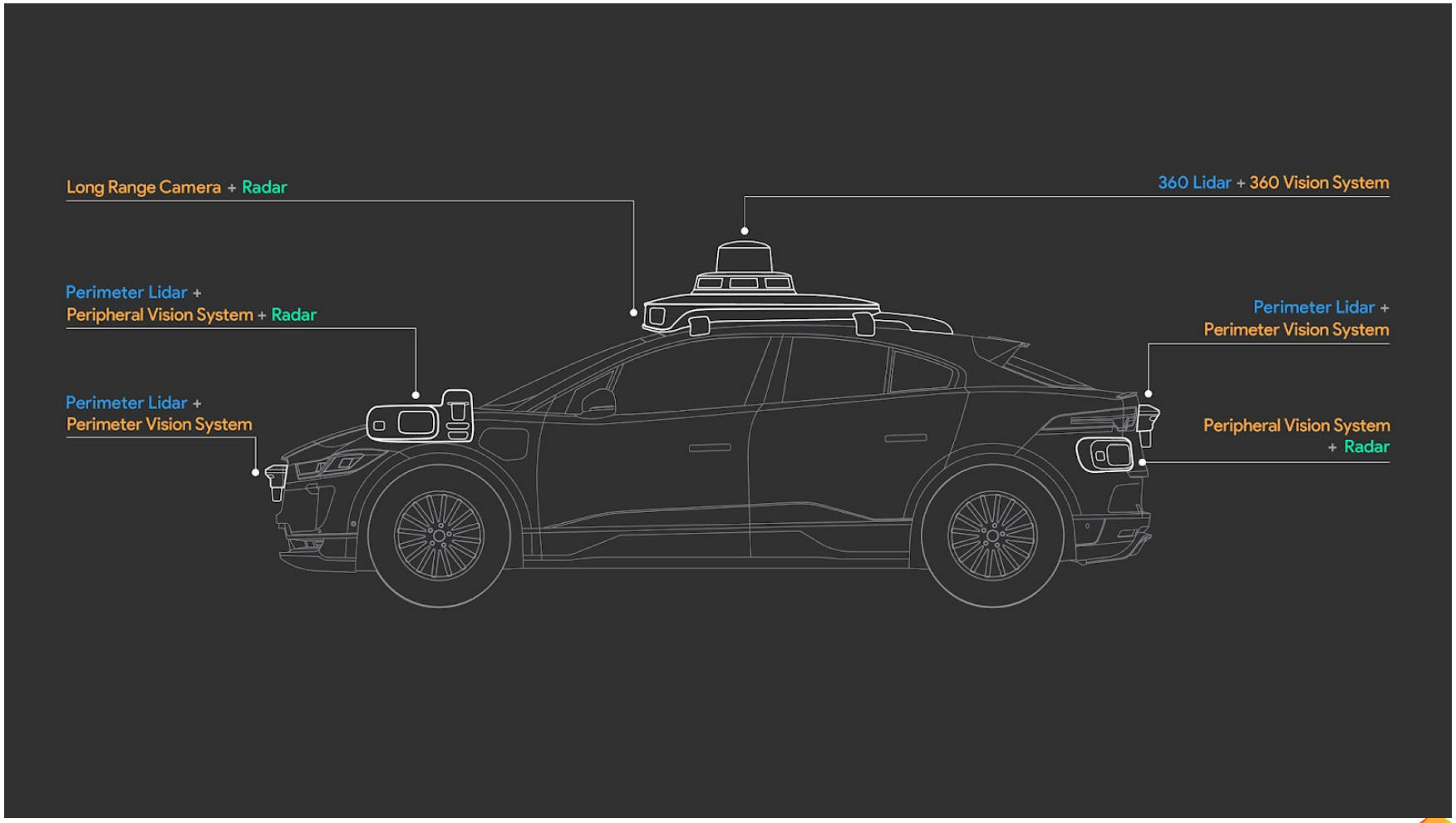
Sensor Suite (Waymo 5th gen)



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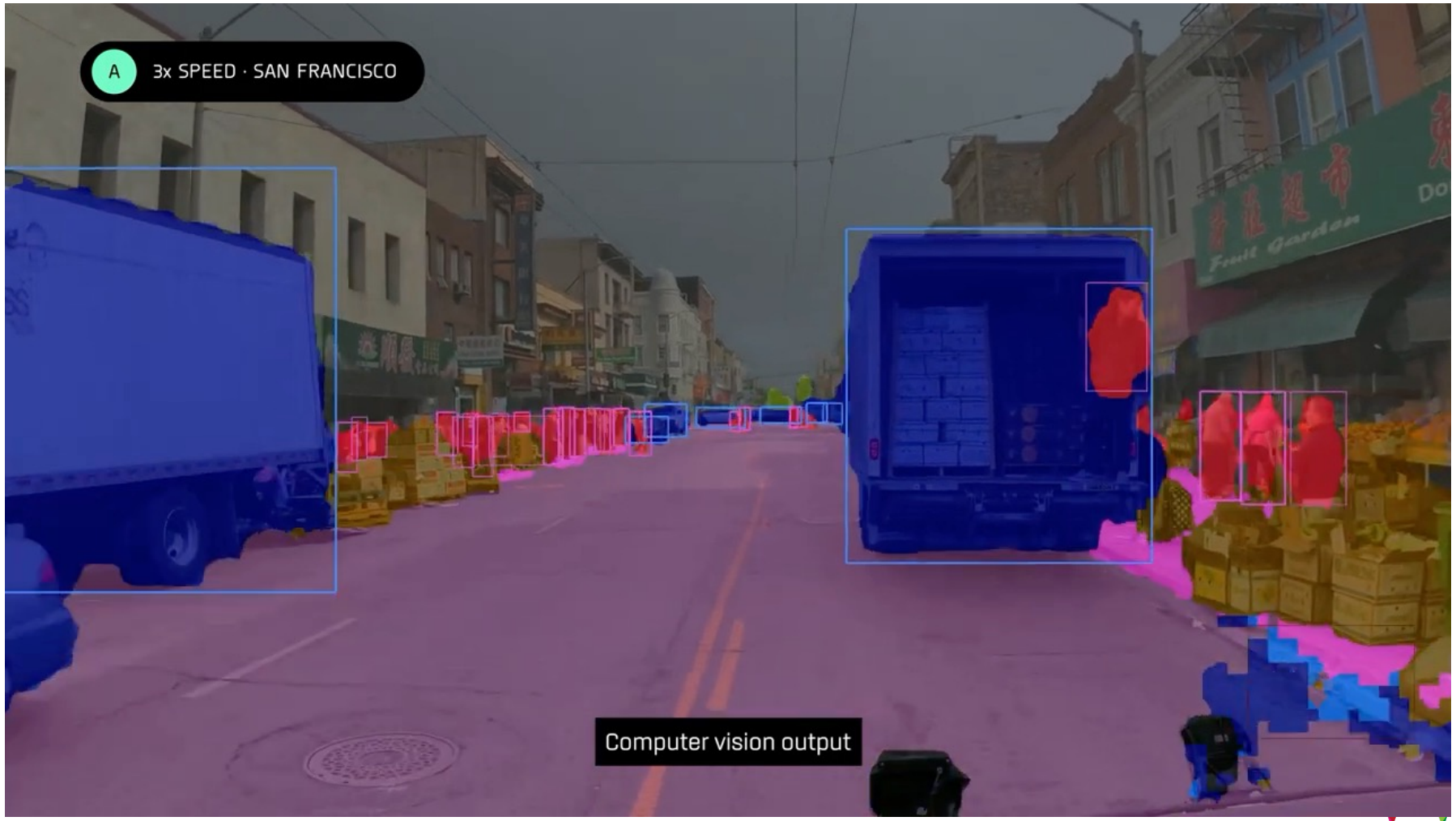
Sensor Fusion



Video Source: https://www.youtube.com/watch?v=5E2NYmgvo3E

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LIDAR

- Velodyne, Hesai, Robosense, Ouster, Luminar, Aeye, Aeva
- Mechanical spinning or solid state

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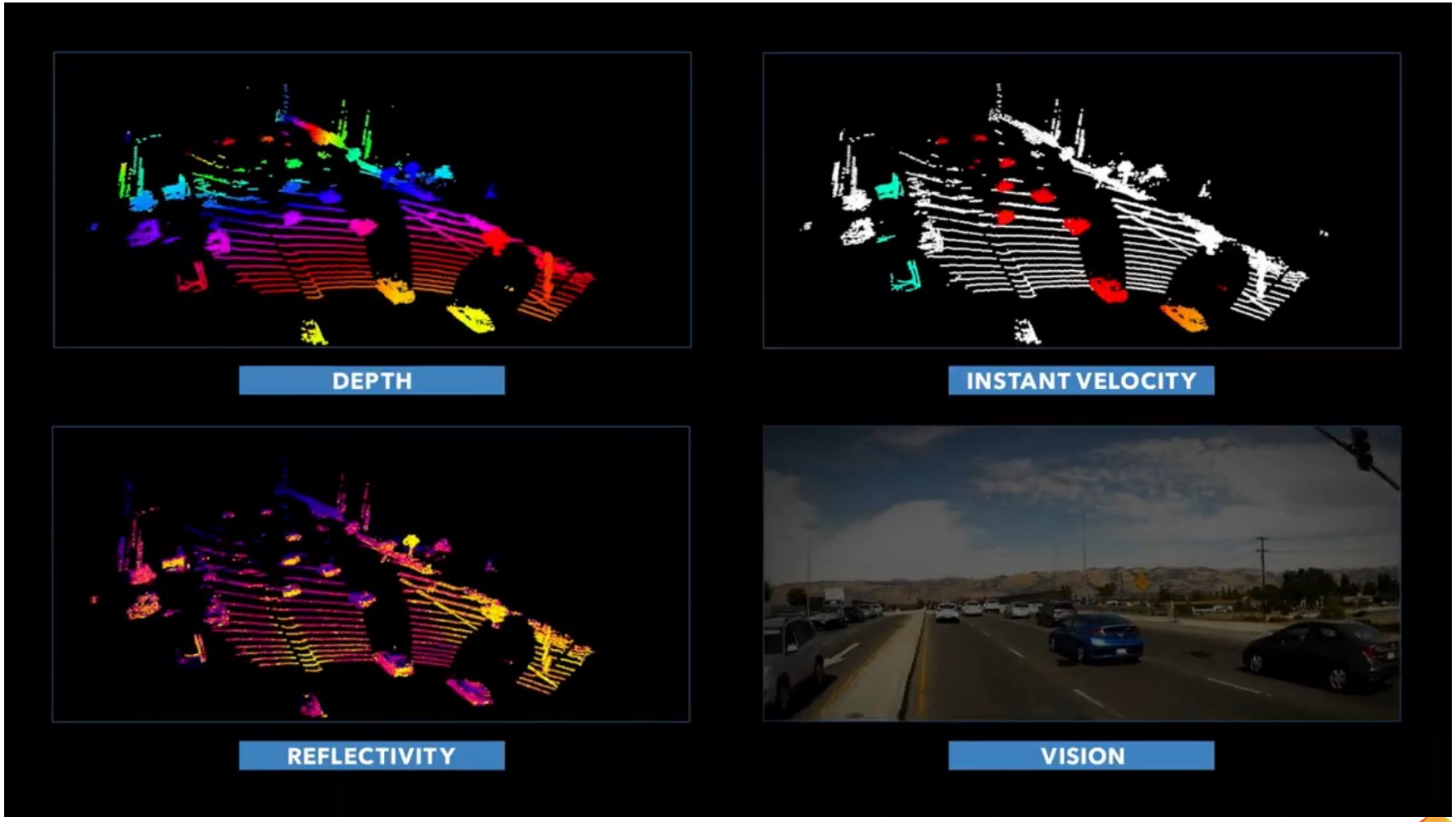
4D LIDAR (Aeva)



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4D Radar / Imaging Radar

- Continental, Smartmicro, Bosch etc.
- Arbe, Radsee, Oculii

- 77-79 GHZ FMCW
- 300m+ range
- High resolution
  - 1° Azimuth- 2° Elevation
  - 7.5 cm range
  - 0.1 m/s doppler

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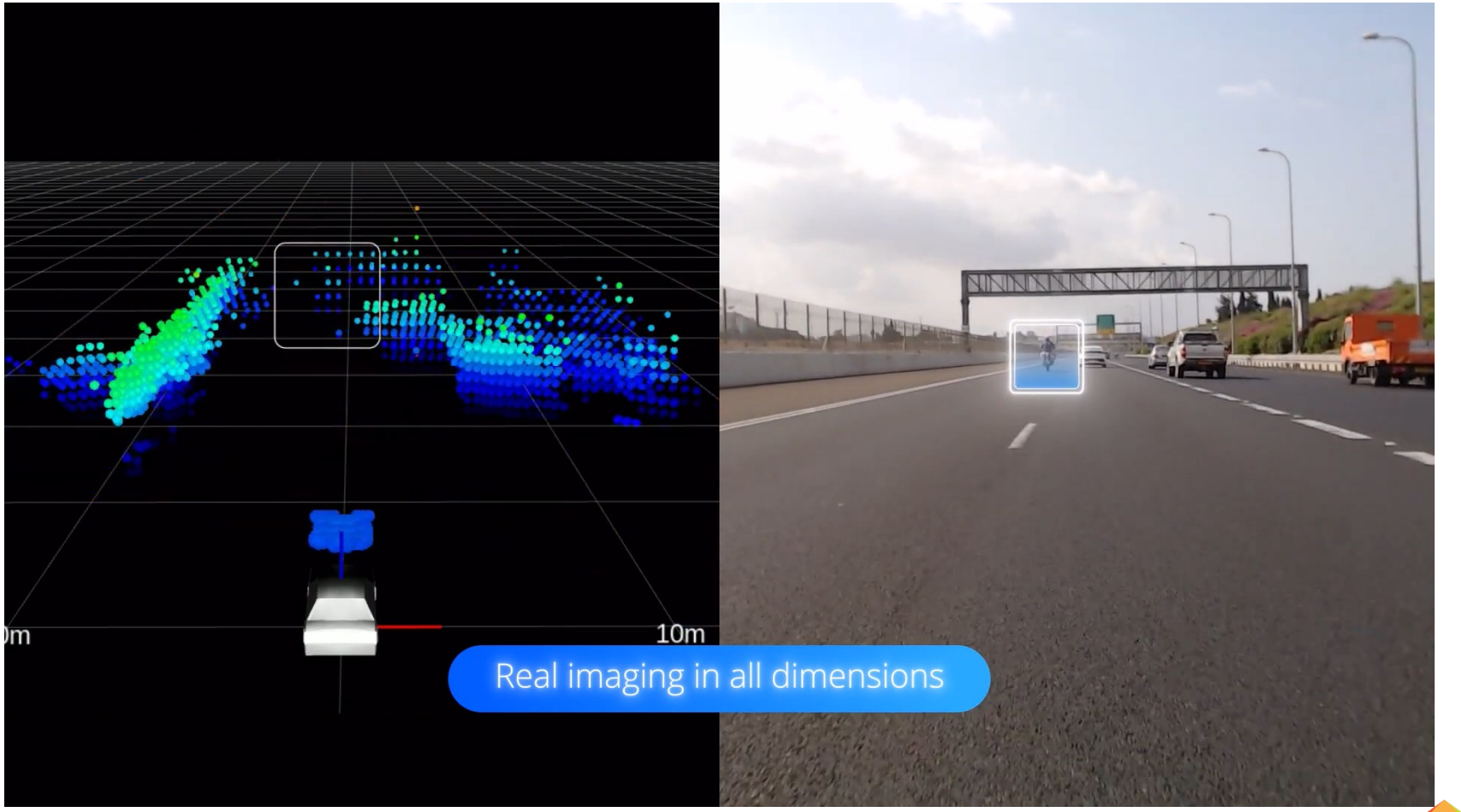
Arbe Imaging Radar



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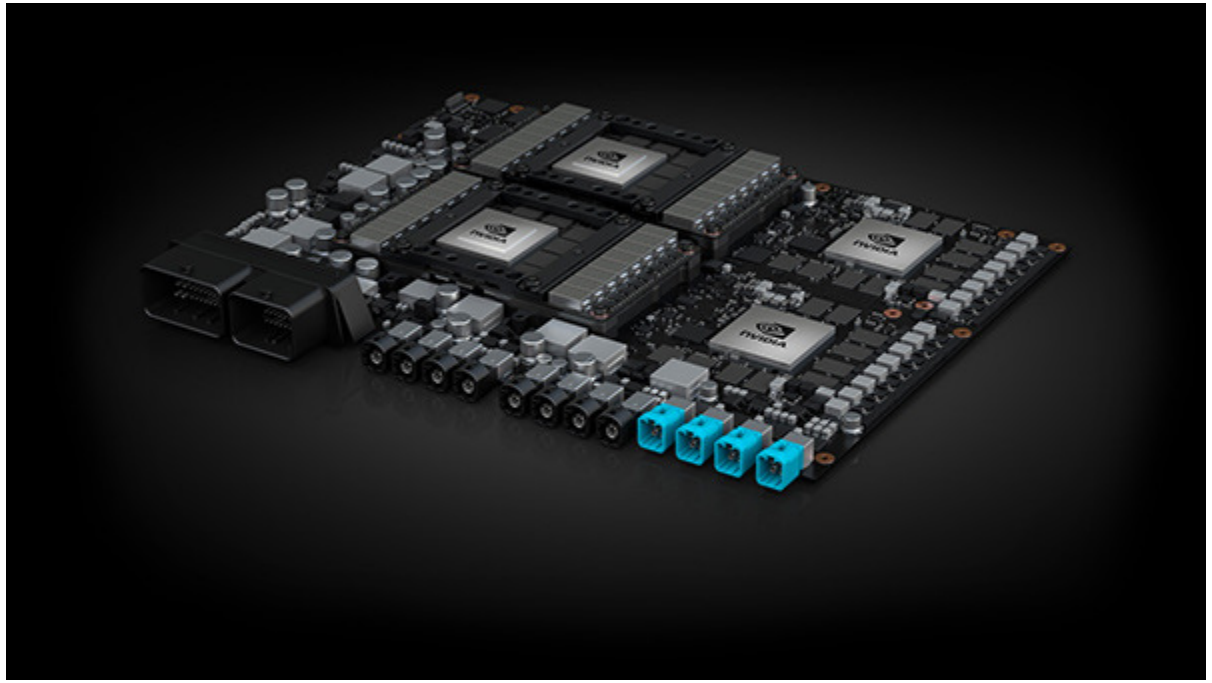
Computing Unit

- For AD (L3/L4):
  - Nvidia Drive AGX
    - 30 TOPS, 100 Watt
  - Nvidia Drive AGX Pegasus
    - 320 TOPS, 500 Watt
  - Nvidia Drive Orin
    - 254 TOPS, 100 Watt
- For ADAS (L0/L1/L2)
  - Renesas, NXP etc.



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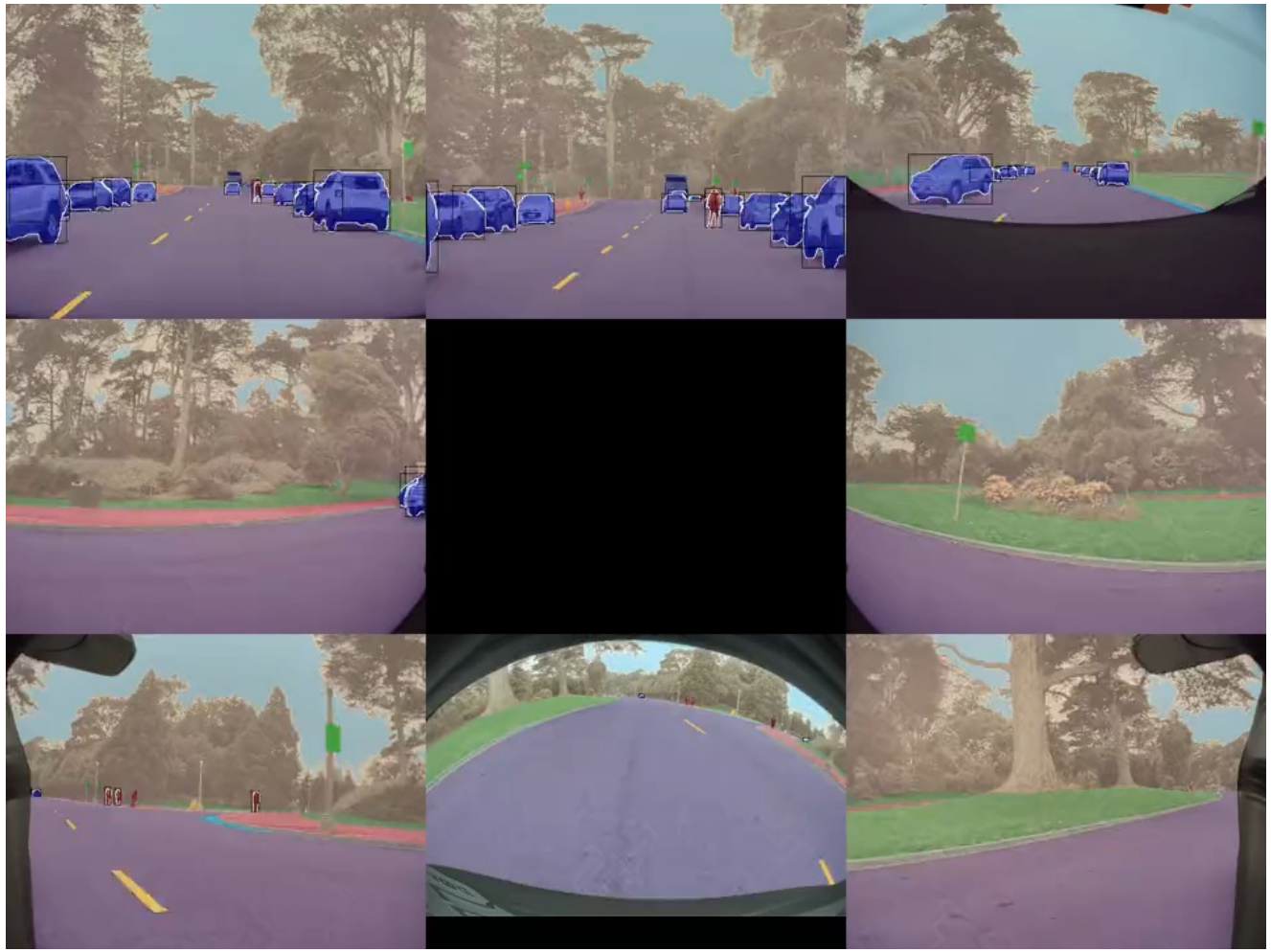
Perception

- What do we want to perceive?
  - OBSTACLES!
    - Are there obstacles around me?
    - Where are the obstacles located?
    - What kind of obstacles are they?
    - What is the speed and direction of the obstacle?
    - Where are the obstacles moving? Where will they be in the future?
  - ROAD
    - What/where is road? Where is lane? Where is drivable? Where is free?
  - SIGNS
    - Traffic signs, traffic lights, on-road signs
  - MISC.
    - Construction zones, construction workers/signs, emergency vehicles, vehicle signals etc.

Perception – AI Algorithms

- Camera
  - Object detection, panoptic segmentation, traffic light /sign detection, lane detection, free-space detection, visual object tracking (instance id), monocular depth estimation
- LIDAR
  - 3D Panoptic segmentation, visual object tracking (instance id), free-space detection
- RADAR
  - Object classiffication

Panoptic Segmentation (Tesla)



https://twitter.com/karpathy/status/1465796331247575042

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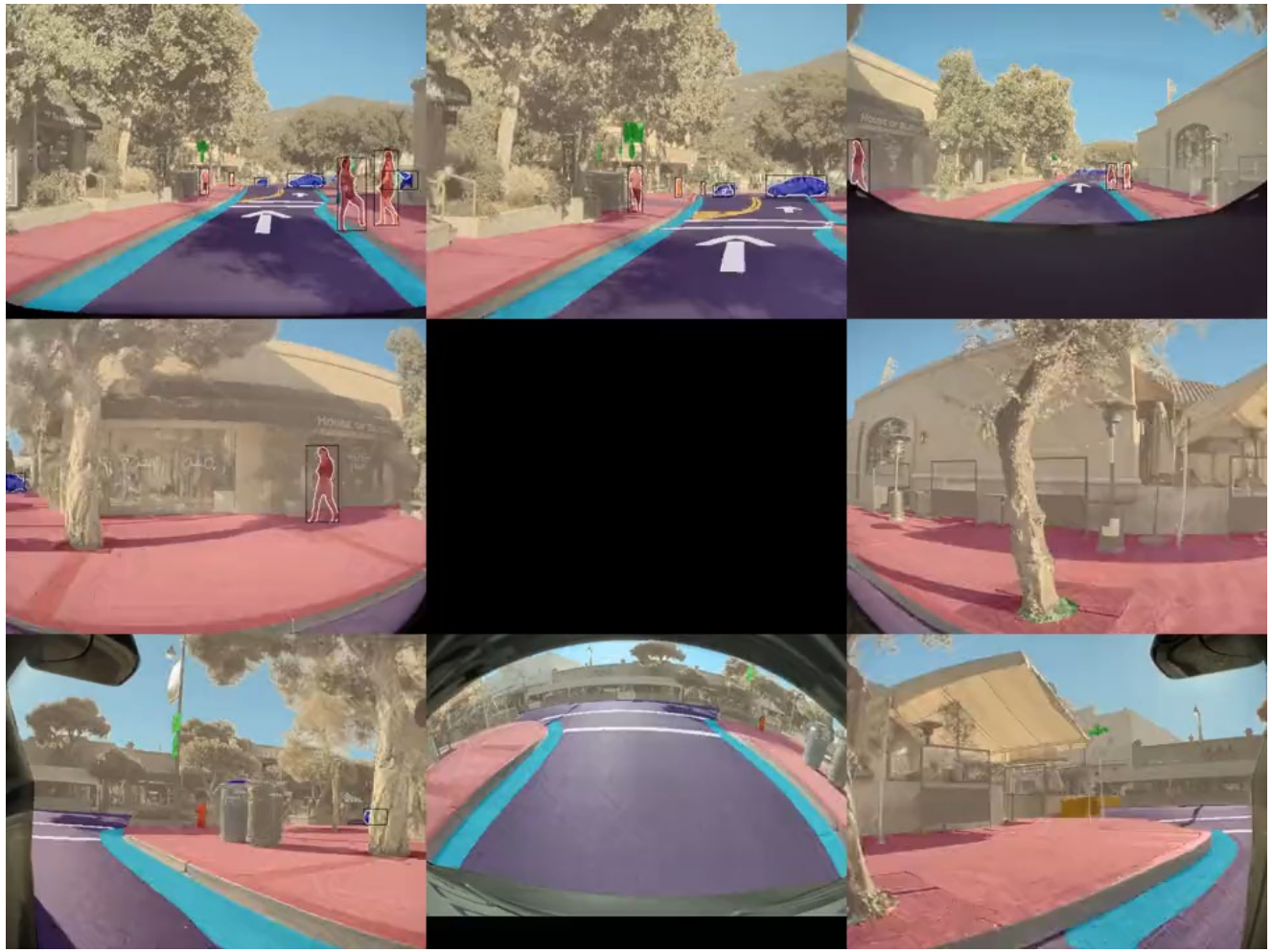
Panoptic Segmentation (Tesla)



https://twitter.com/karpathy/status/1465796331247575042

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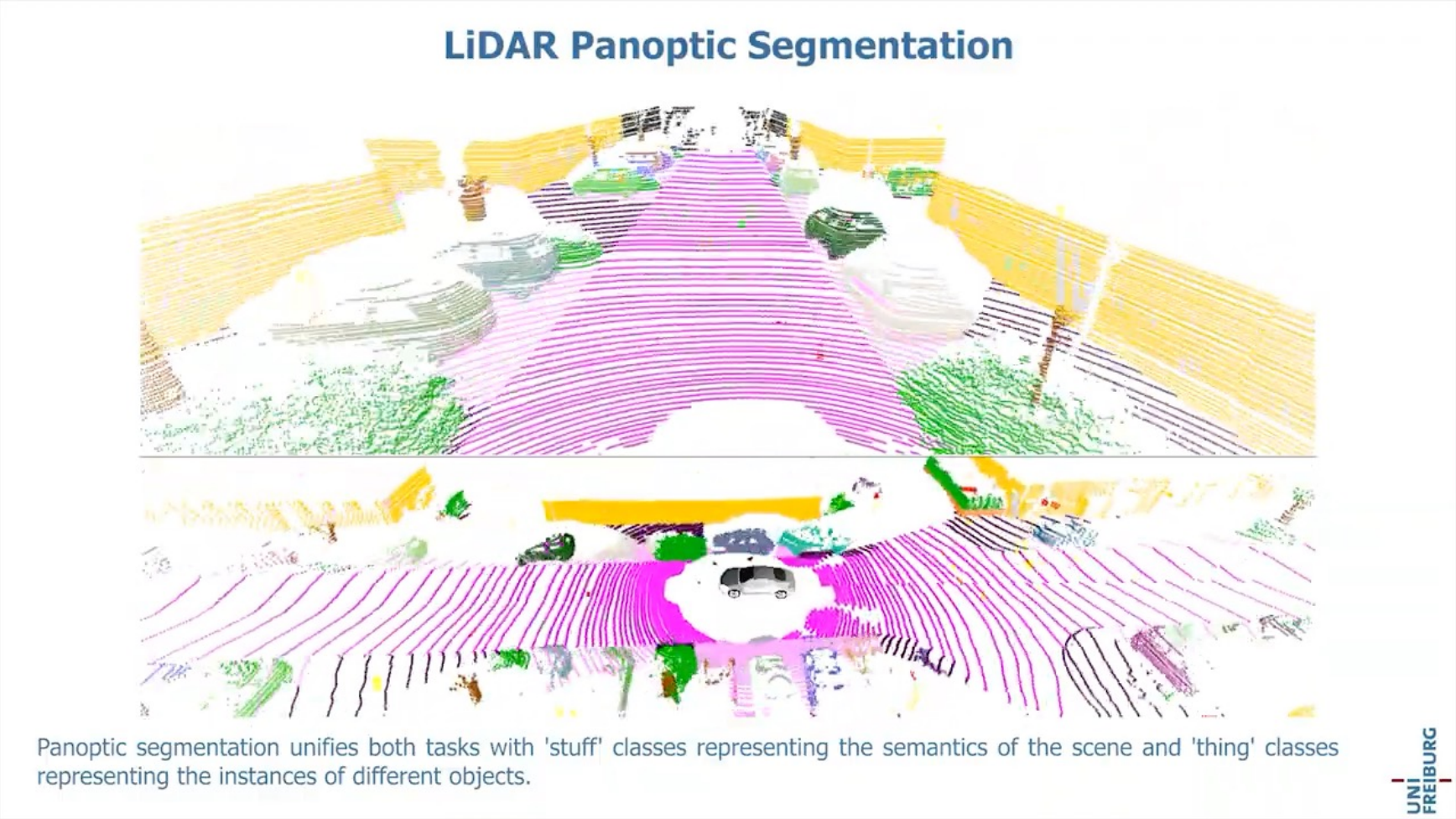
LIDAR Panoptic Segmentation



Panoptic segmentation unifies both tasks with 'stuff' classes representing the semantics of the scene and 'thing' classes representing the instances of different objects.

EfficientLPS: Efficient LiDAR Panoptic Segmentation Paper: https://arxiv.org/abs/2102.08009

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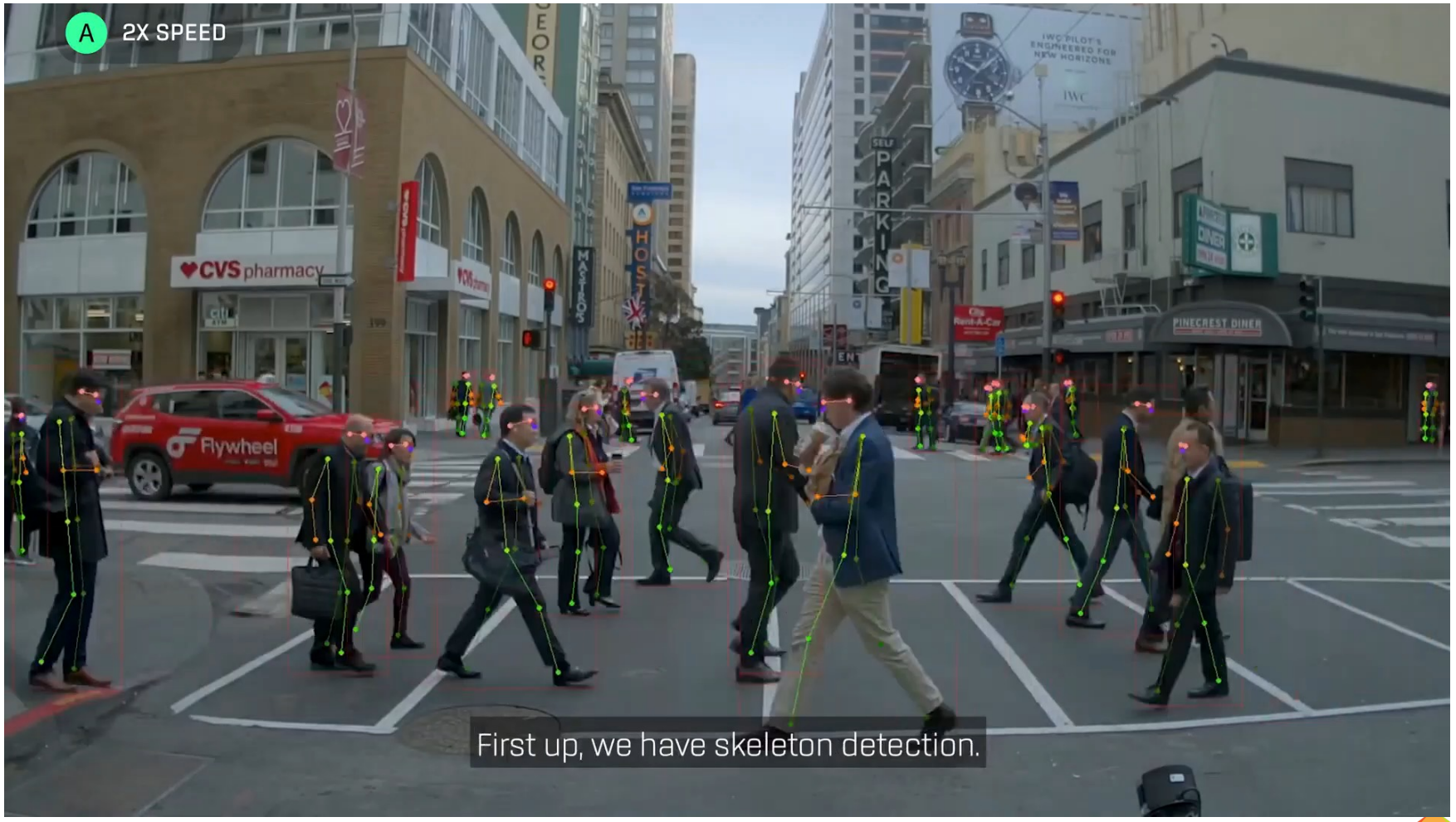
Pedestrian Analysis (Zoox)



Video taken from Zoox: https://www.youtube.com/watch?v=BVRMh9NO9Cs

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Technologies / Libraries

- OS: Ubuntu or QNX
- Middleware: ROS or ROS2
- Model Training: Pytorch
- Model Deployment: TensorRT
- Programming Lang: C++

Why ROS?

- Message passing, executable launching, visualization, data recording, pre-programmed data-types, transforms, etc. for robots
- Easy to learn
- Lots of documentation, training, community resources
- Comes ready with a lot of tools and libraries easily available
- Lots of available code
- Support for simulators
- Support for drivers

Shortcommings of ROS

- Shortcommings of the publish/subscribe abstraction
  - Serialization & data transfer overhead
  - Poor use of CPU due to thread architecture
- Many of facilities provided by ROS are not suitable for real-time
  - Dynamic memory allocation:
    - Both runtime structures and APIs make pervasive use of dynamically allocated memory
    - Some of the user-facing APIs rely on dynamically-allocated memory.
  - Inter-process-Communication
    - The default mechanism for IPC in ROS is TCP
    - Reliability at cost of unbounded latency.
  - Priority management
    - Low-priority messages steal CPU time away from high-priority messages.
    - Callback and publication queues are all FIFO, newly-arrived high-priority messages cannot preempt existing tasks, even if they are lower priority.
- Lack of determinism
  - Execution reordering due to jitter
  - Non-atomic message delivery due to peer-to-peer message delivery
  - Dropped data caused by overflowing subscriber queues

Vagili, Lessons Learned Building a Self DrivingCar on ROS, 2019

ROS vs ROS2*

ROS

- a single robot
- workstation-class computational resources
- no real-time requirements
- excellent network connectivity
- applications in research, mostly academia; and
- maximum flexibility, with nothing prescribed or proscribed

ROS 2

- Teams of multiple robots
- Small embedded platforms
- Real-time system (time critical)
  - Memory allocation, scheduling, QoS
- Non-ideal networks
- Production environments
- Prescribed patterns for building and structuring systems

* https://design.ros2.org/articles/why_ros2.html

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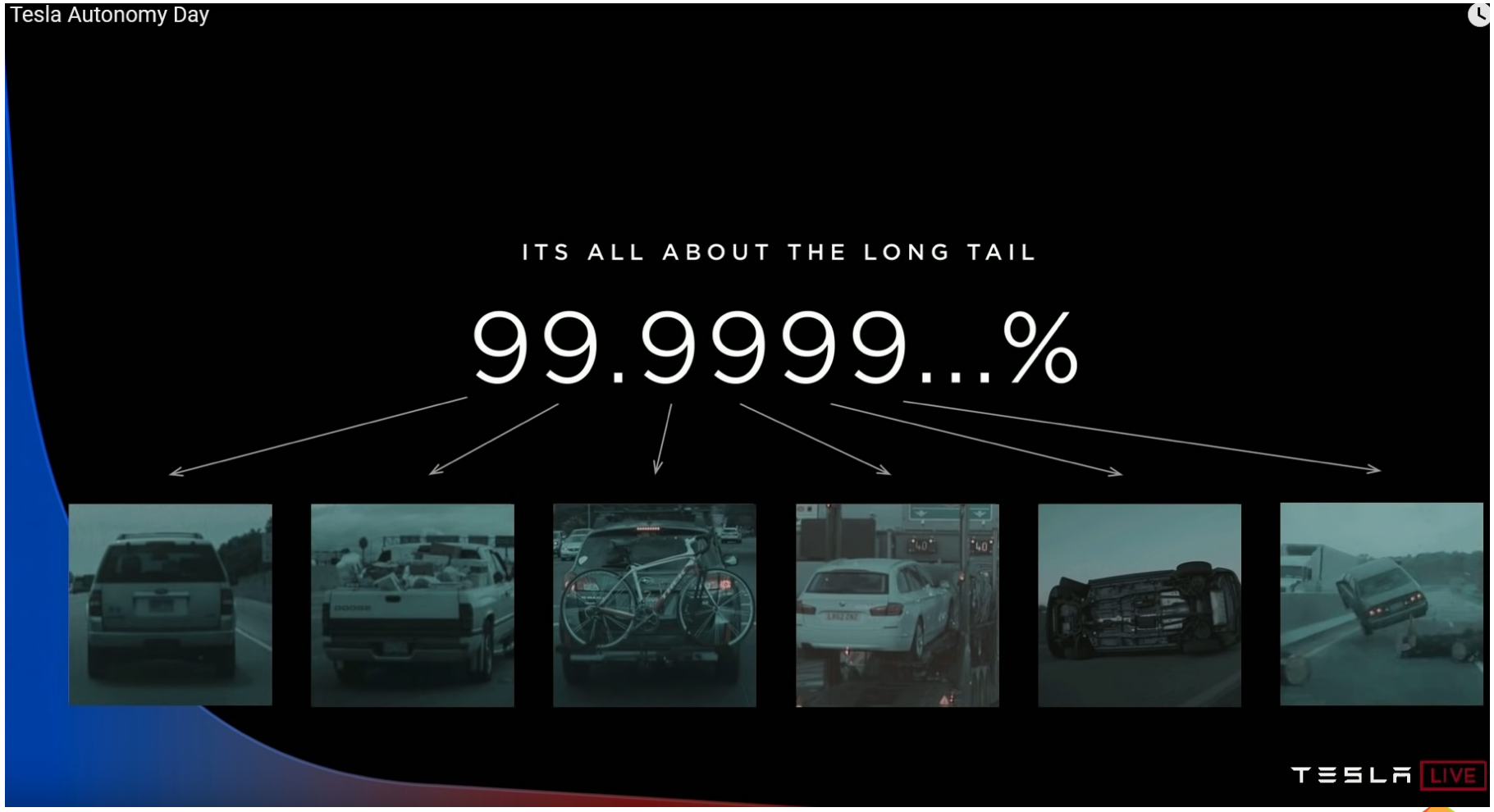
How to achieve extreme robustness?

- How do we deal with any kind of
  - Objects
  - Events
  - Weather conditions
- How do we rigorously test?
- Are there any standards and regulations?

It’s All About the Long Tail Events!



Taken from TESLA Autonomy day 2019 video: https://www.youtube.com/watch?v=Ucp0TTmvqOE

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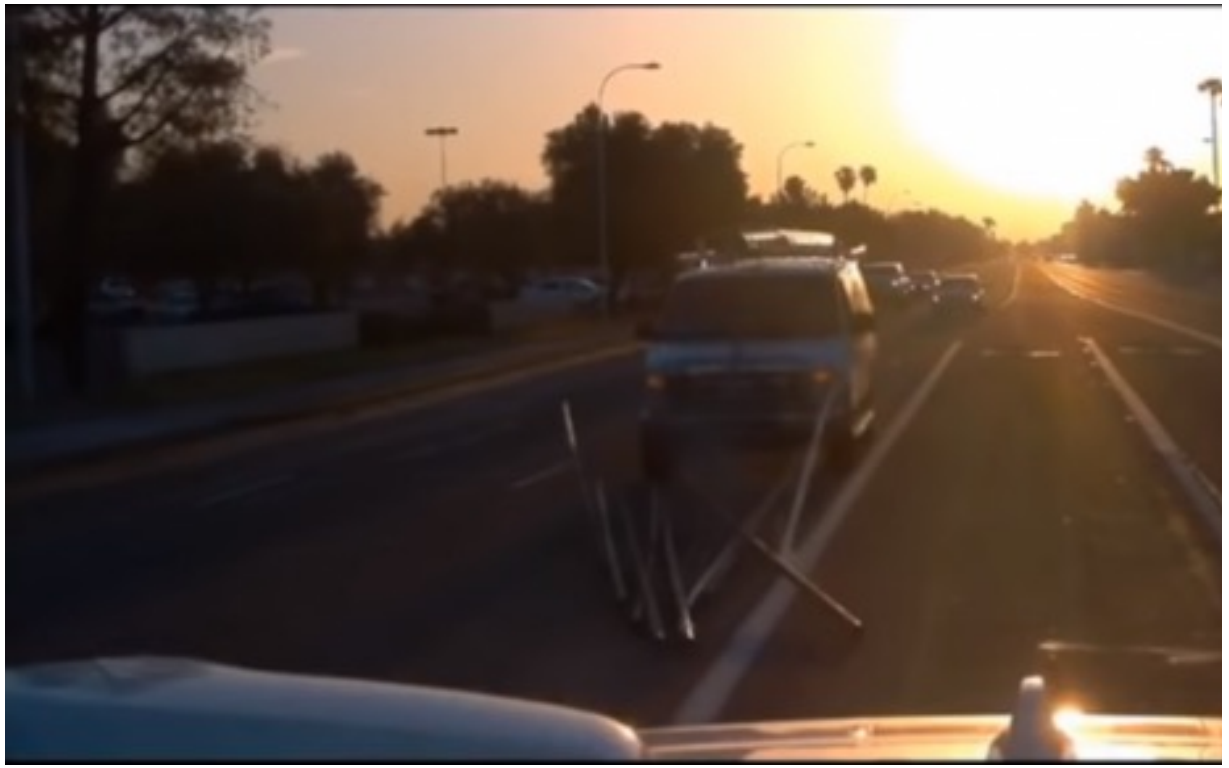
Long Tail



Images are from Drago Anguelov (Waymo) - MIT Self-Driving Cars: https://www.youtube.com/watch?v=Q0nGo2-y0xY

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How To Deal With Long Tail?

- Massive amount of data
- Simulation and synthetic data generation
- Auto labeling
- Active learning
- Non-ML algorithms

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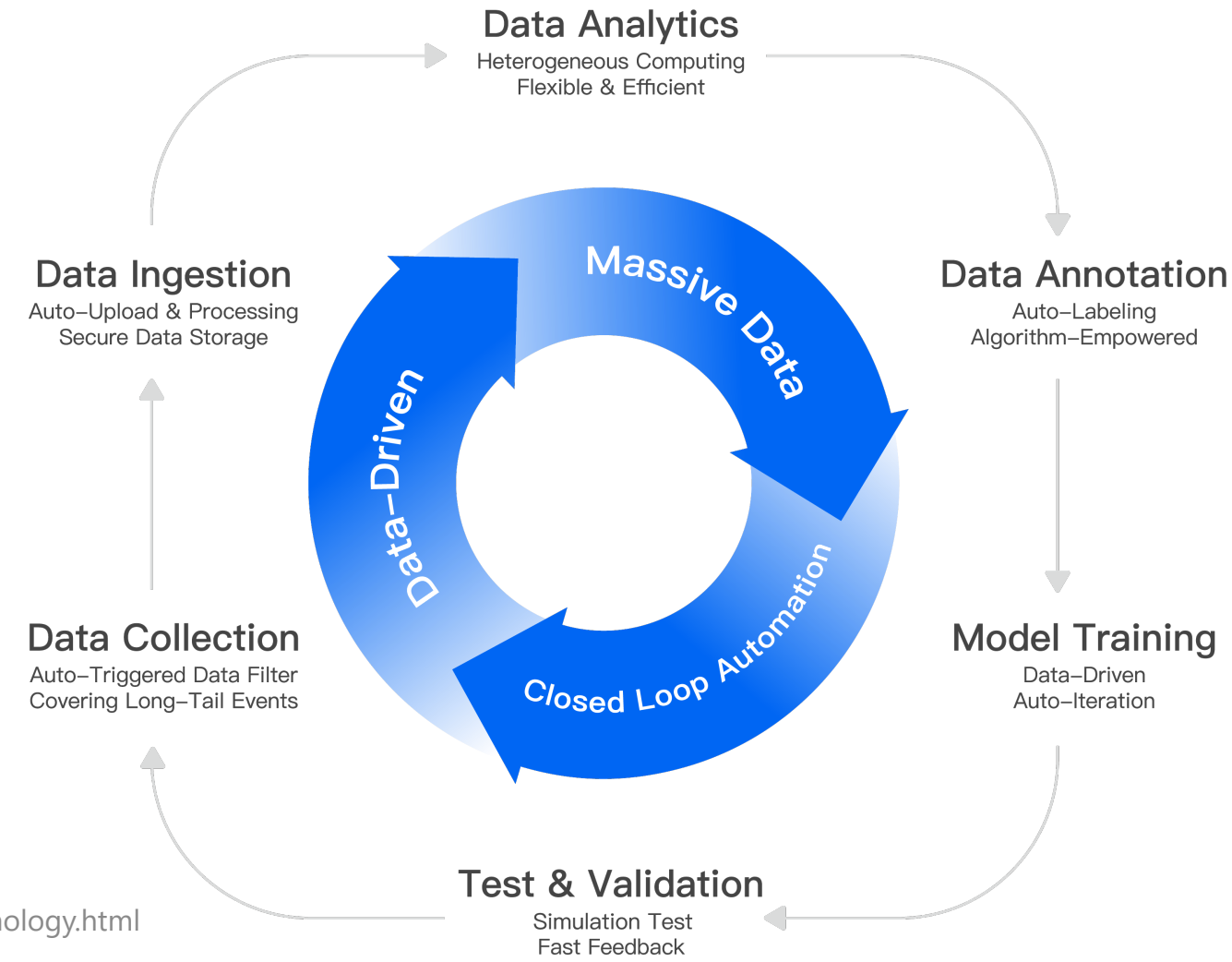
Autonomous Driving - Closed Loop Automation (*momenta.ai*)



https://momenta.ai/en/technology.html

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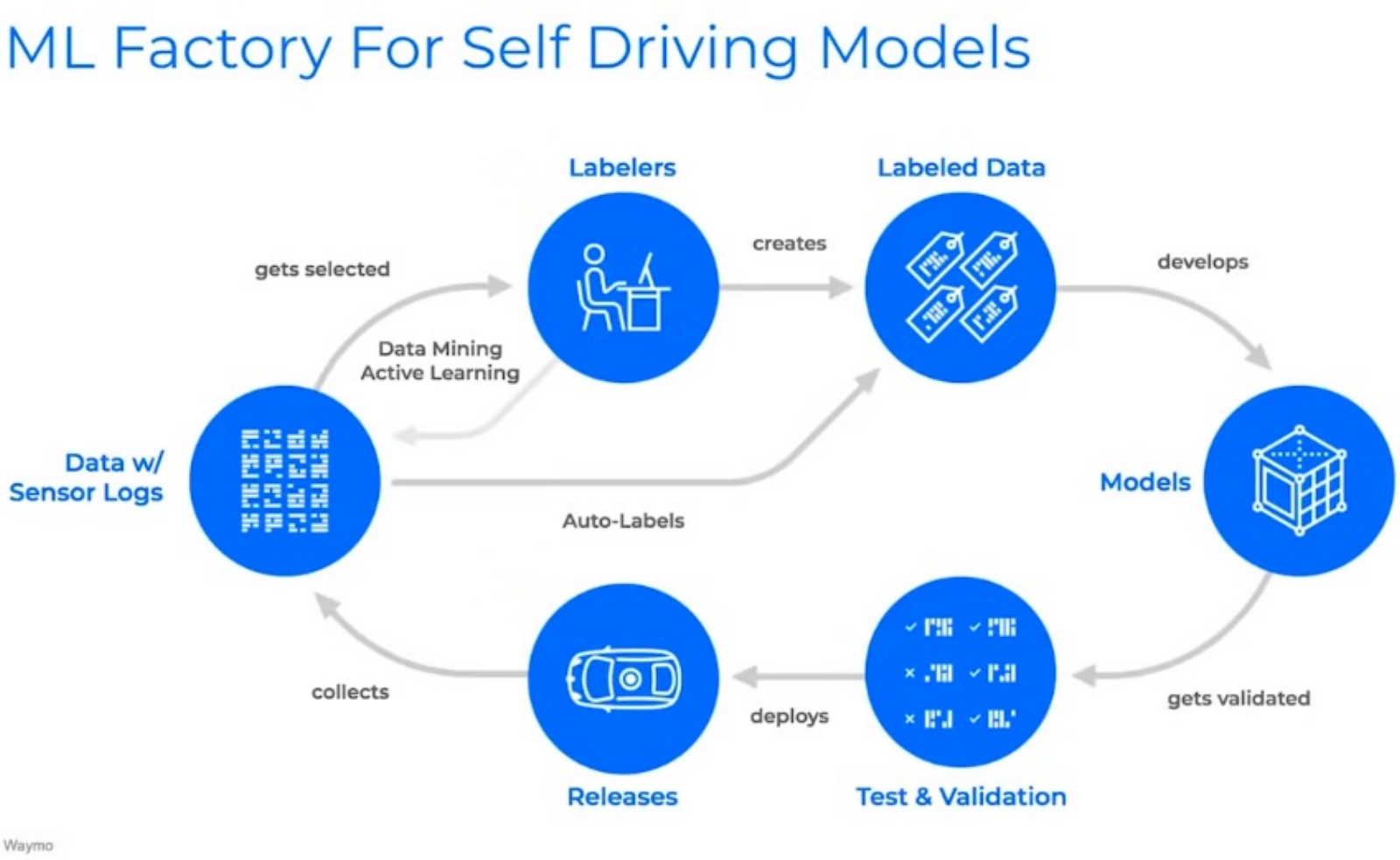
Waymo – Closed Loop Automation



Drago Anguelov (Waymo) - MIT Self-Driving Cars : https://youtu.be/Q0nGo2-y0xY

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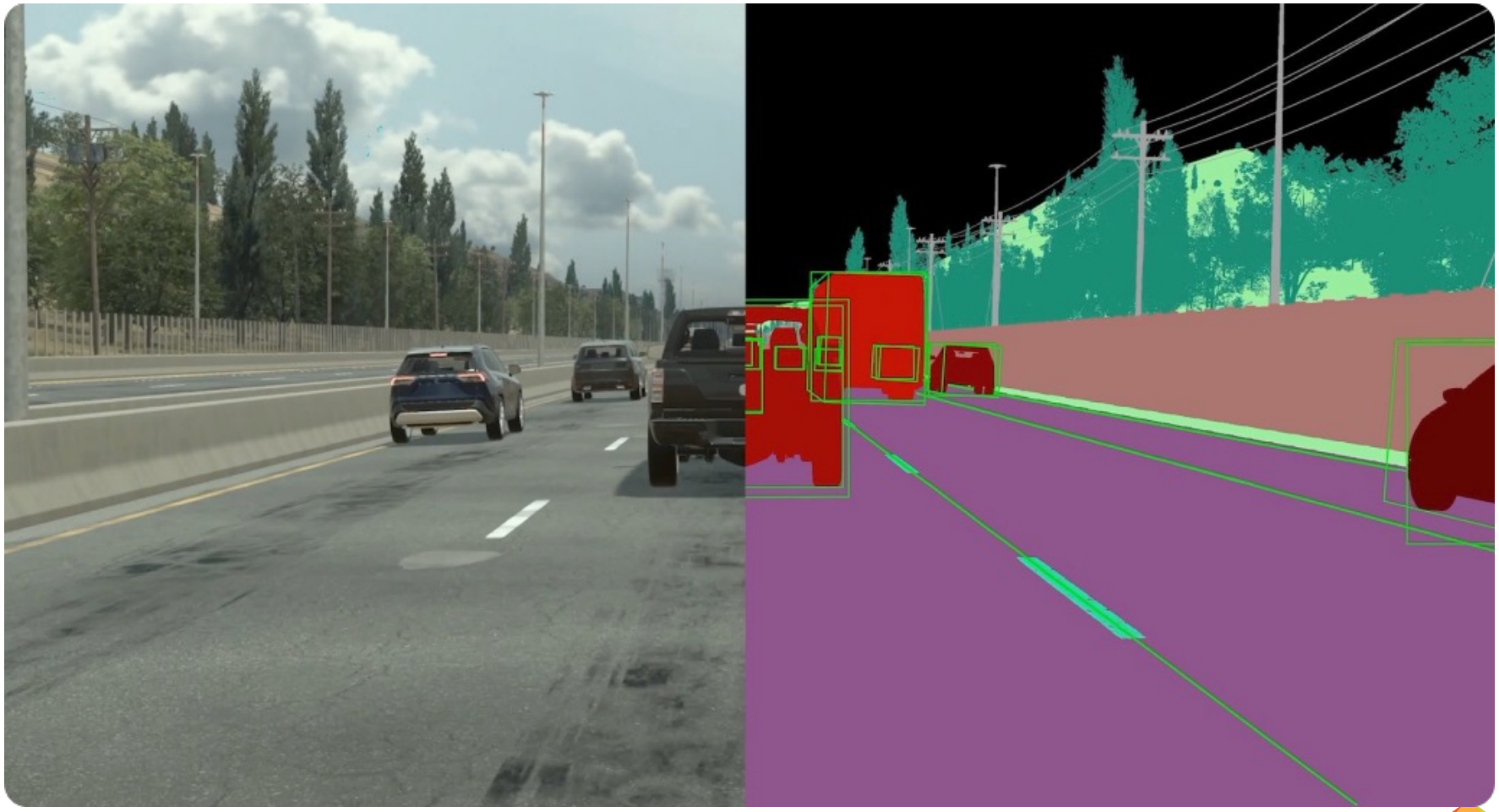
Simulation and Synthetic Data Generation



Pictures taken from: https://www.appliedintuition.com/

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Simulation and Synthetic Data Generation

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Simulation and Synthetic Data Generation

Pictures taken from: https://www.appliedintuition.com/

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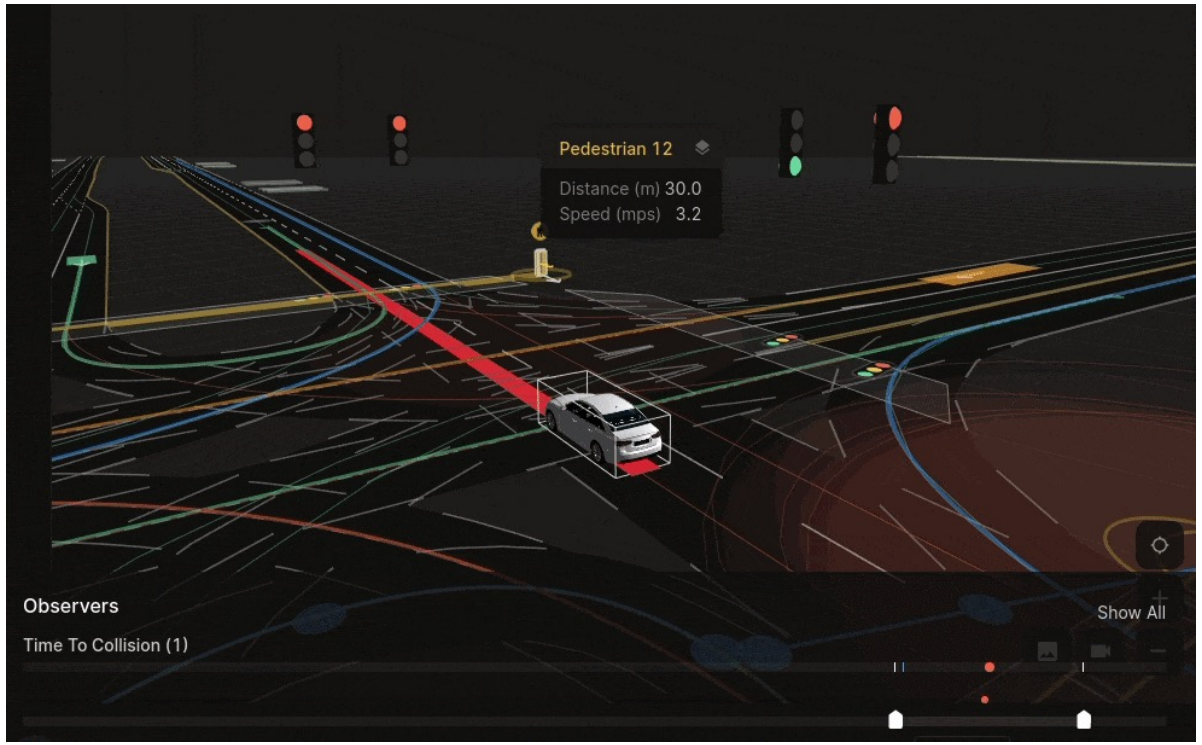
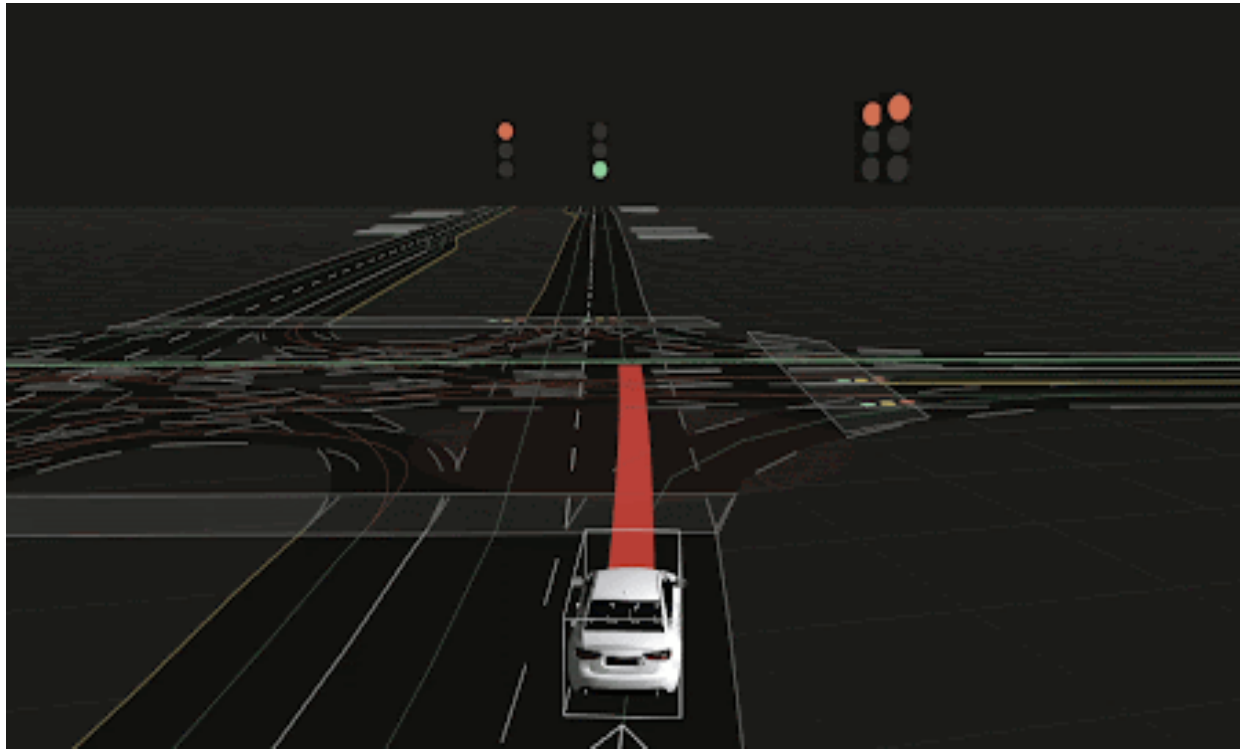
Testing via Simulation

Video Source: https://www.youtube.com/watch?v=zpwIRcJMMbc

Testing via Simulation





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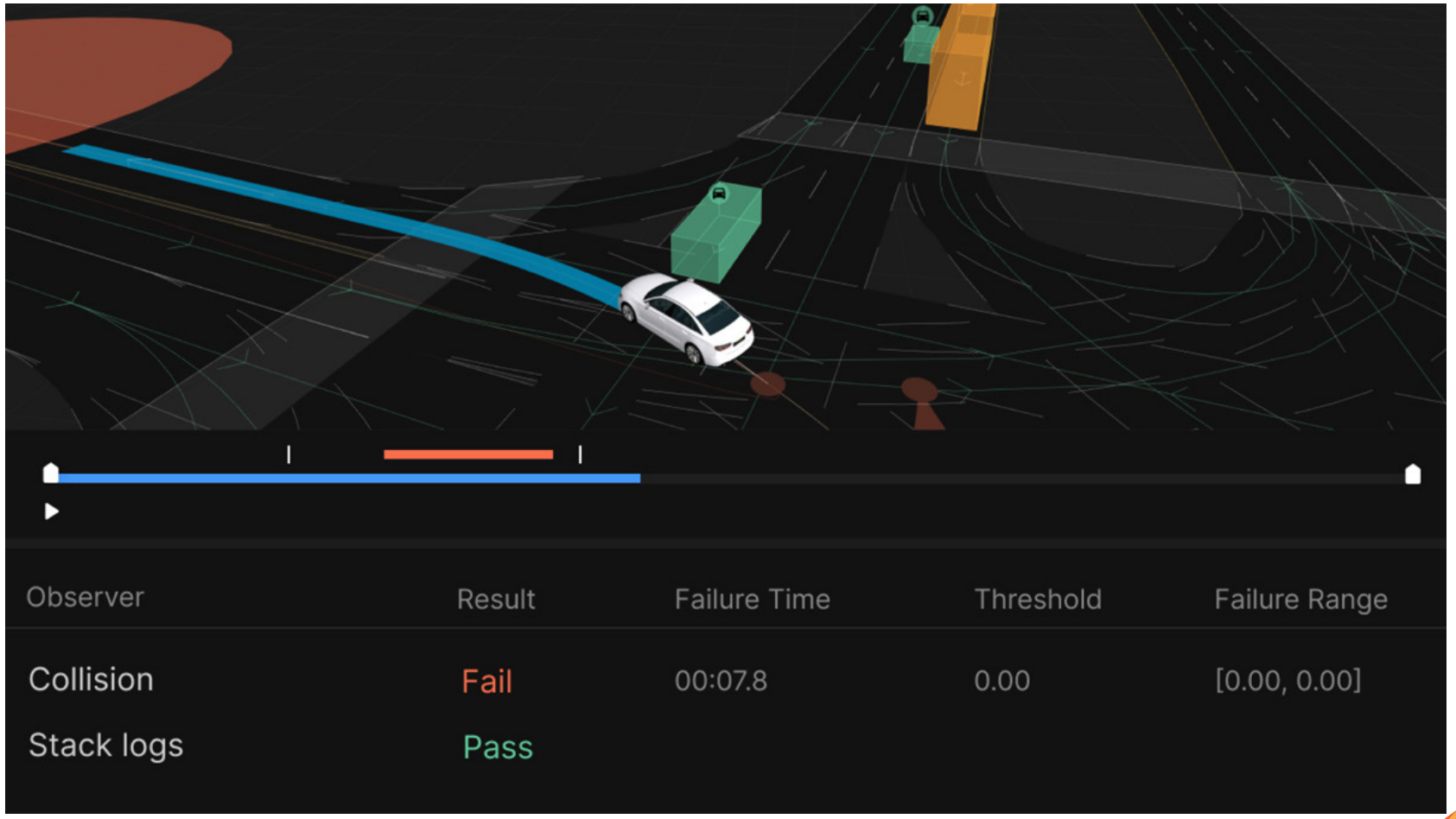
Testing via Simulation



Pictures taken from: https://www.appliedintuition.com/

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TESLA – Simulation

Taken from TESLA AI Day 2021: https://www.youtube.com/watch?v=j0z4FweCy4M

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Nvidia Drive Sim

https://www.youtube.com/watch?v=gPaFgNEF82Q

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Cruise – Simulation

https://www.youtube.com/watch?v=qOuROC4dSbw

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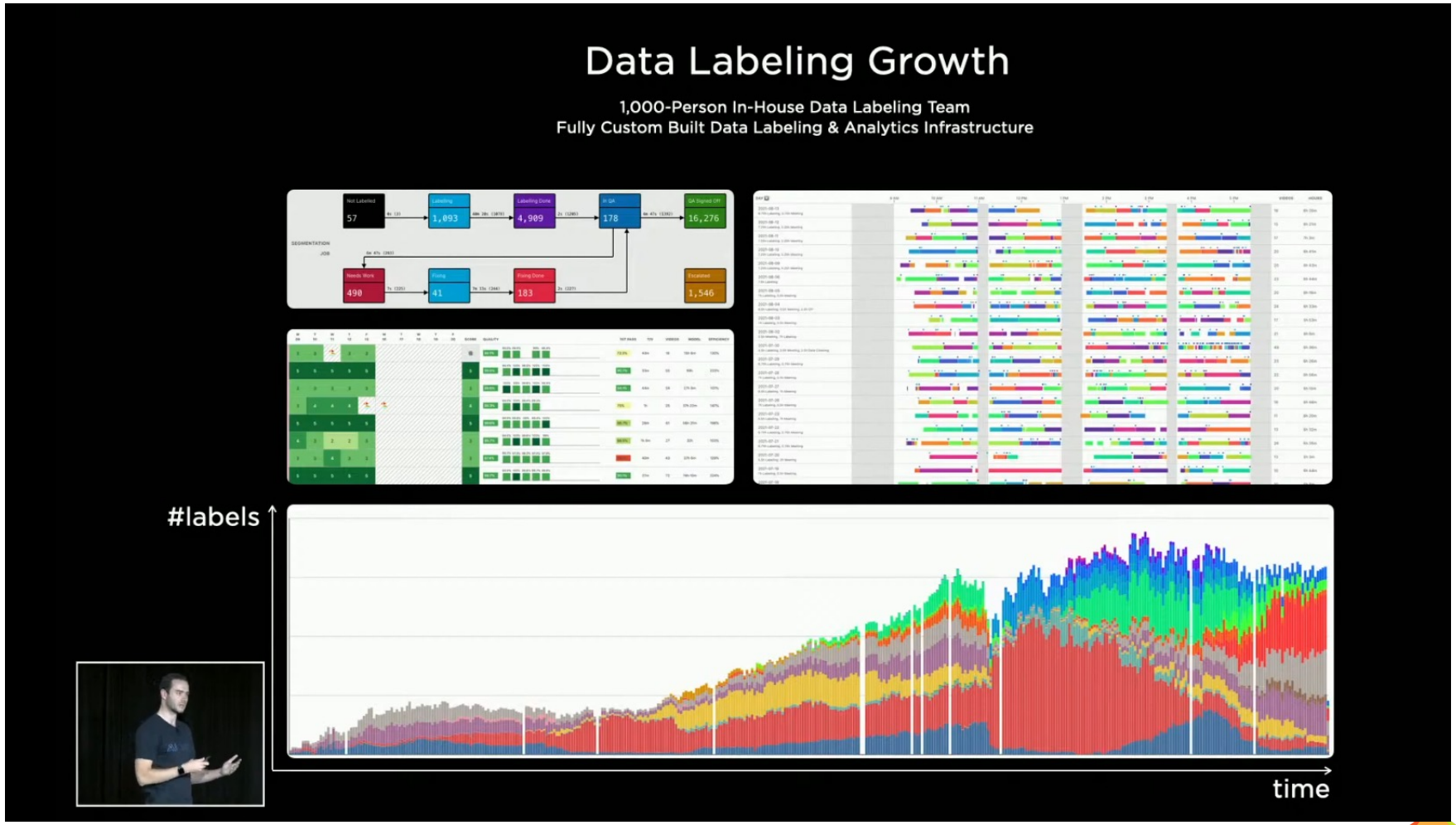
Simulation and Synthetic Data Generation

- Paid
  - Applied Intuition (https://www.appliedintuition.com/)
  - Cognata (https://www.cognata.com/)
  - Nvidia Drive Sim (https://developer.nvidia.com/drive/drive-sim)

- Free
  - SVL Simulator (https://www.svlsimulator.com/)
  - Intel Carla (https://carla.org/)

Manual Labeling (Tesla)



Taken from TESLA AI Day 2021: https://www.youtube.com/watch?v=j0z4FweCy4M

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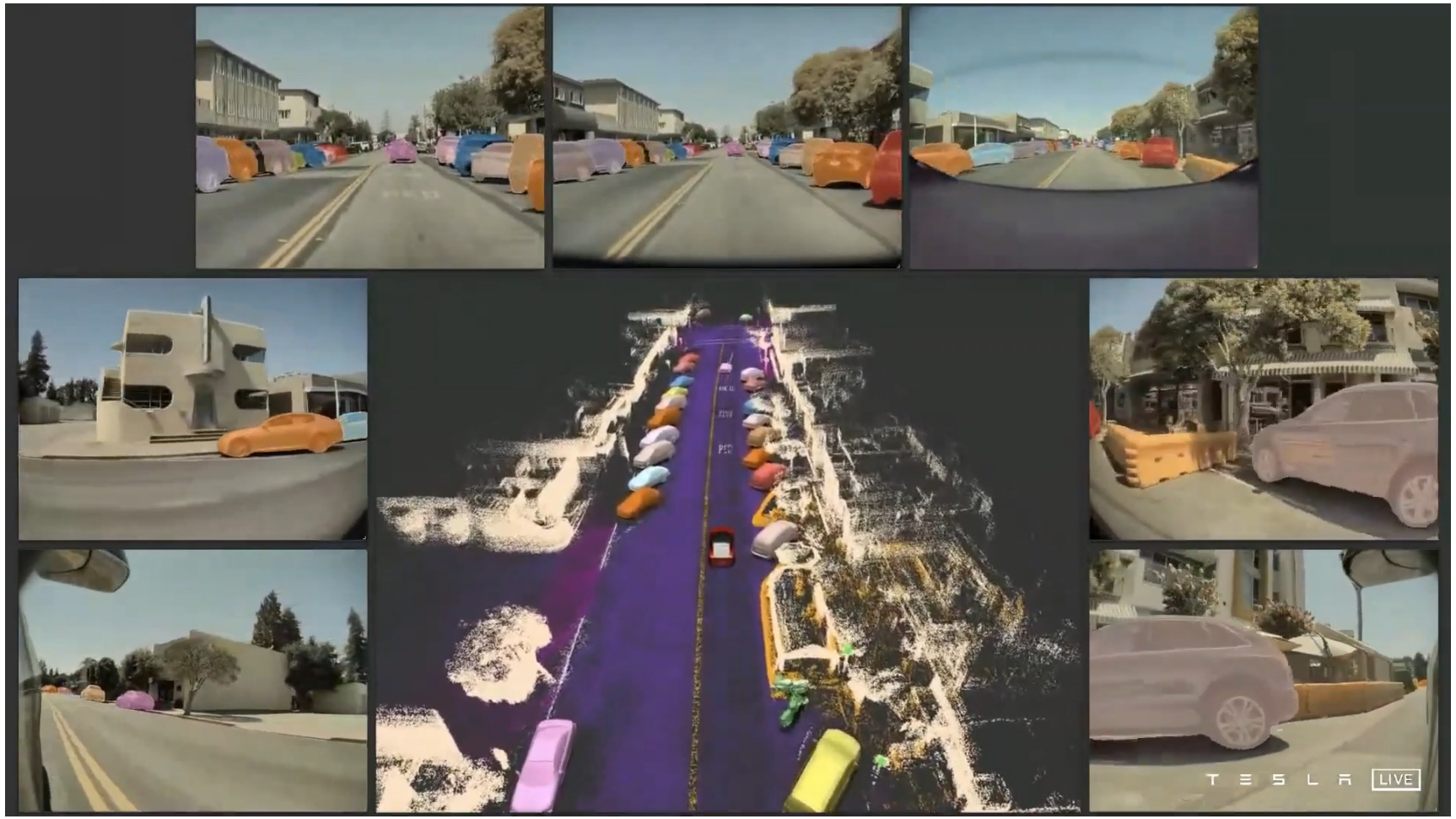
Auto Labeling (Tesla)



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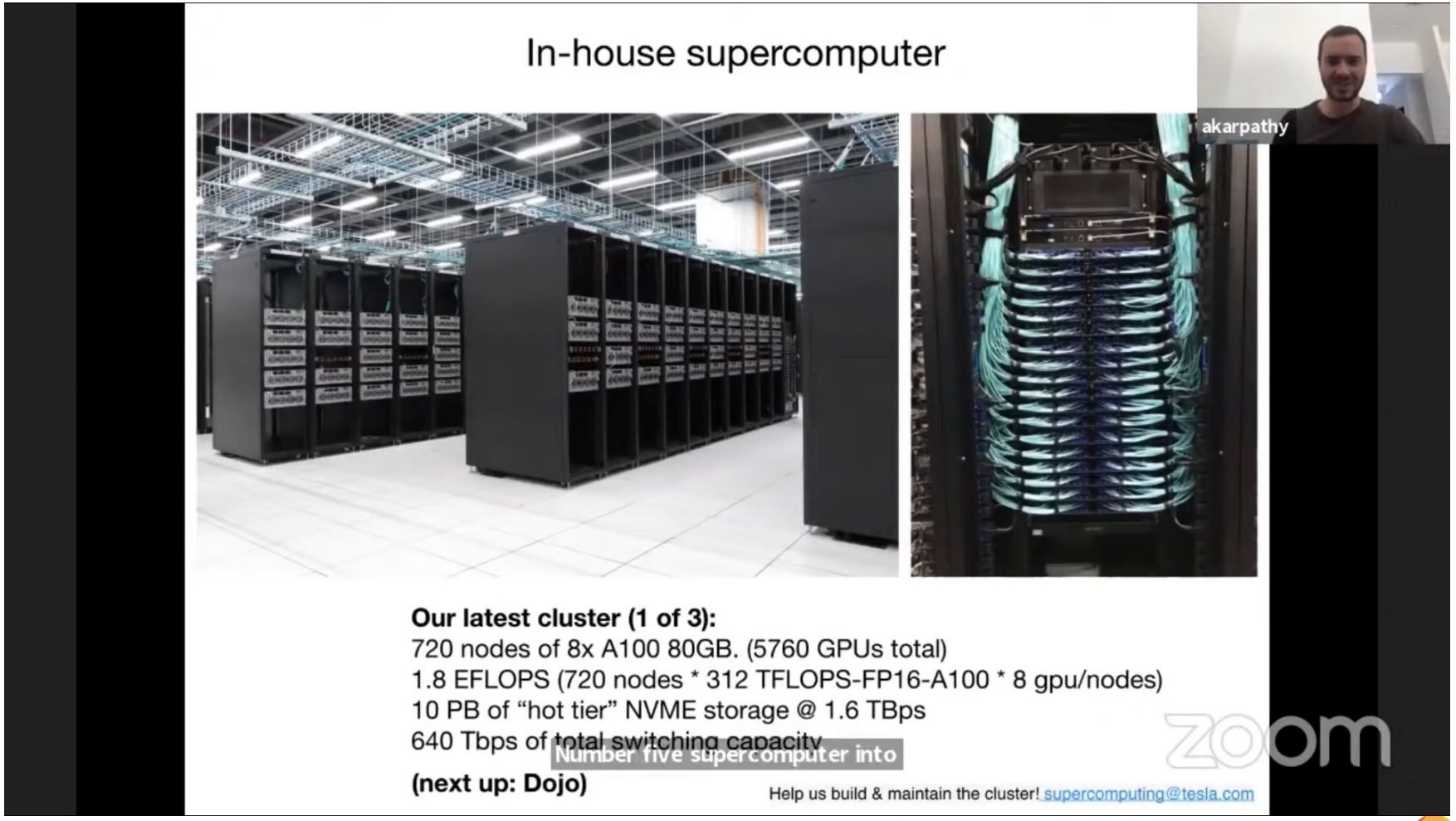
How Tesla Trains Their Models ?



Taken from CVPR 2021 Workshop on Autonomous Driving Keynote Speech by Andrej Karpathy

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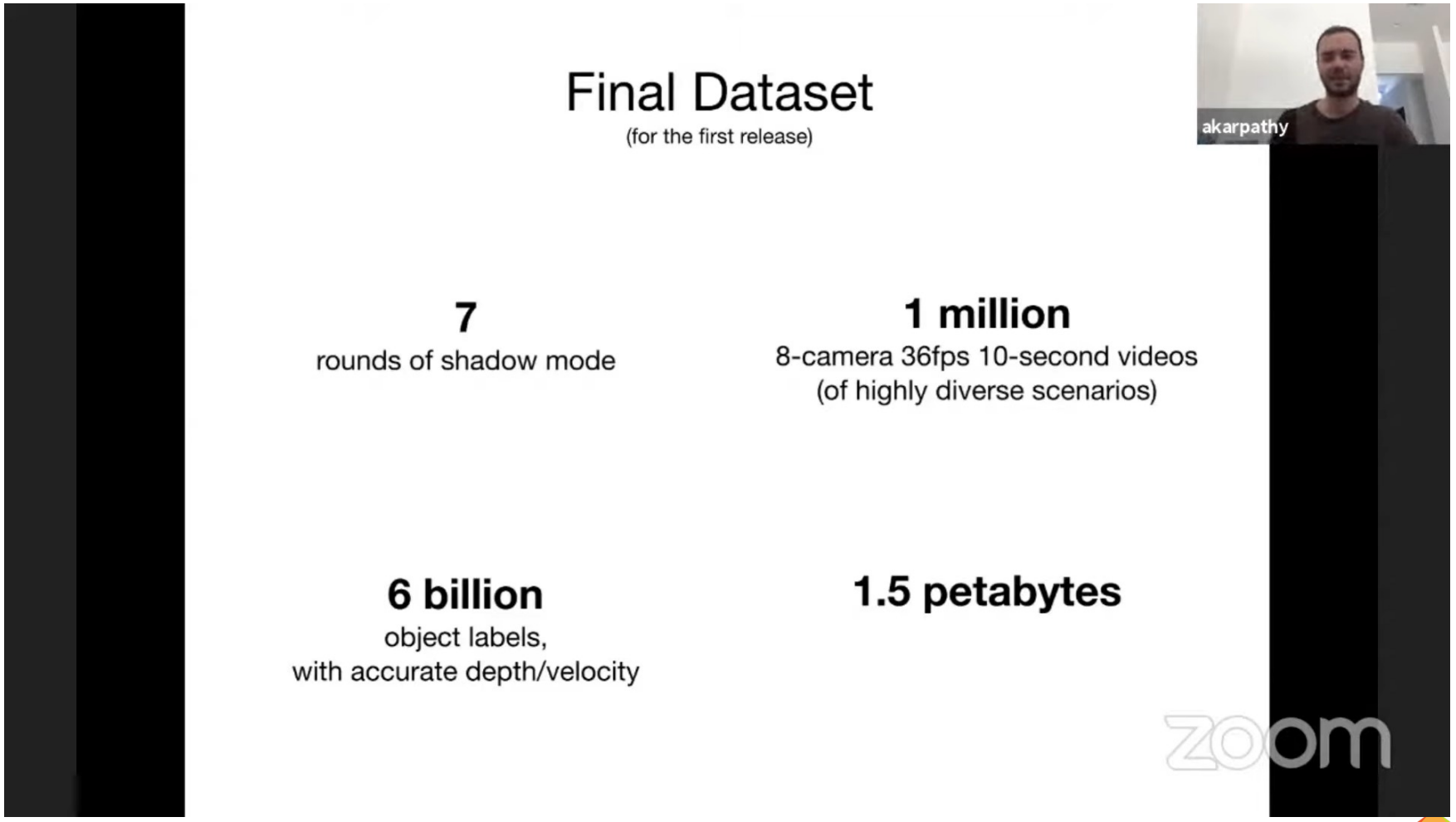

Taken from CVPR 2021 Workshop on Autonomous Driving Keynote Speech by Andrej Karpathy

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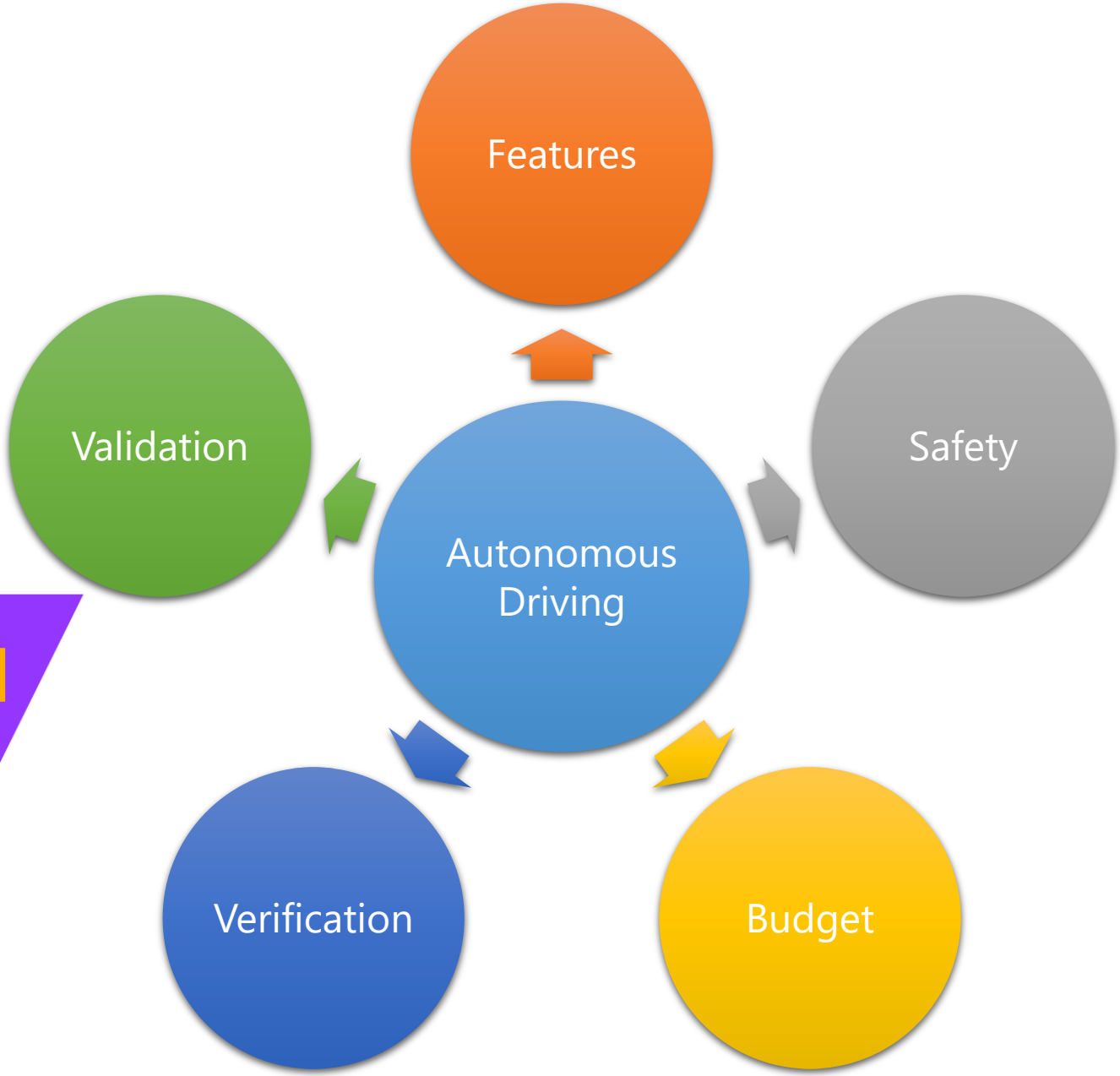
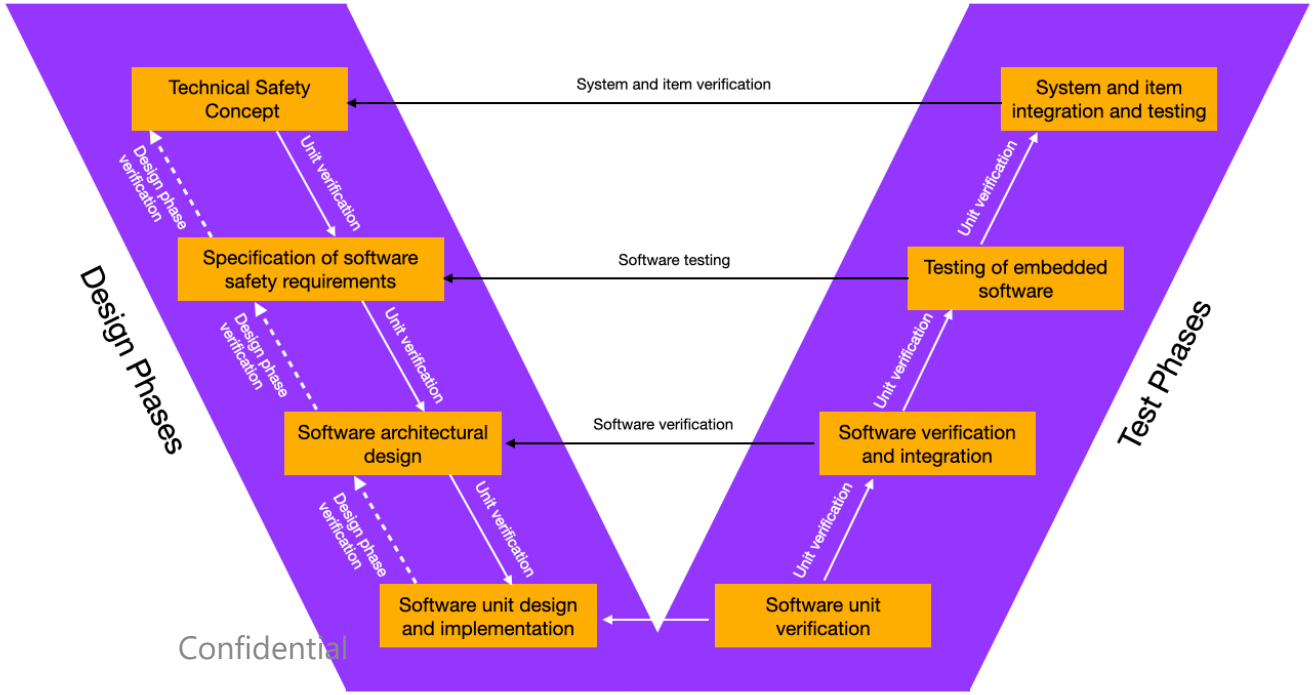
Autonomous Driving and Commercialization

- ISO 26262 and etc.



V-Model (ISO 26262)



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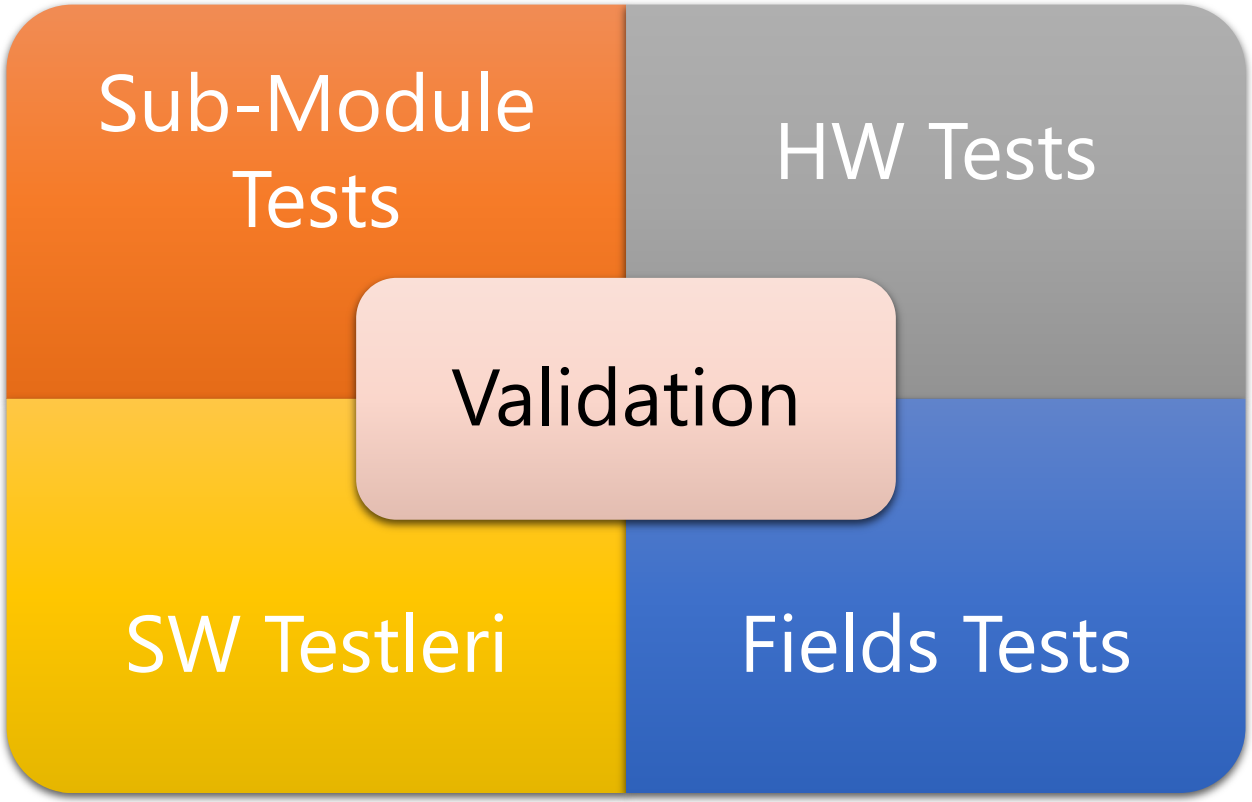
Commercialization → Verification and Validation

- ISO 26262 and Others



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Standards and Regulations

- Main Standards
  - SOTIF (IISO/WD PAS 21448)
  - **ISO 26262**
  - ISO/SAE DIS 21434 (Road Vehicles – Cybersecurity Eng.) (Draft)
- Sample Regulations
  - UN ECE R130 – LDWS
  - UN ECE R131 – AEBS

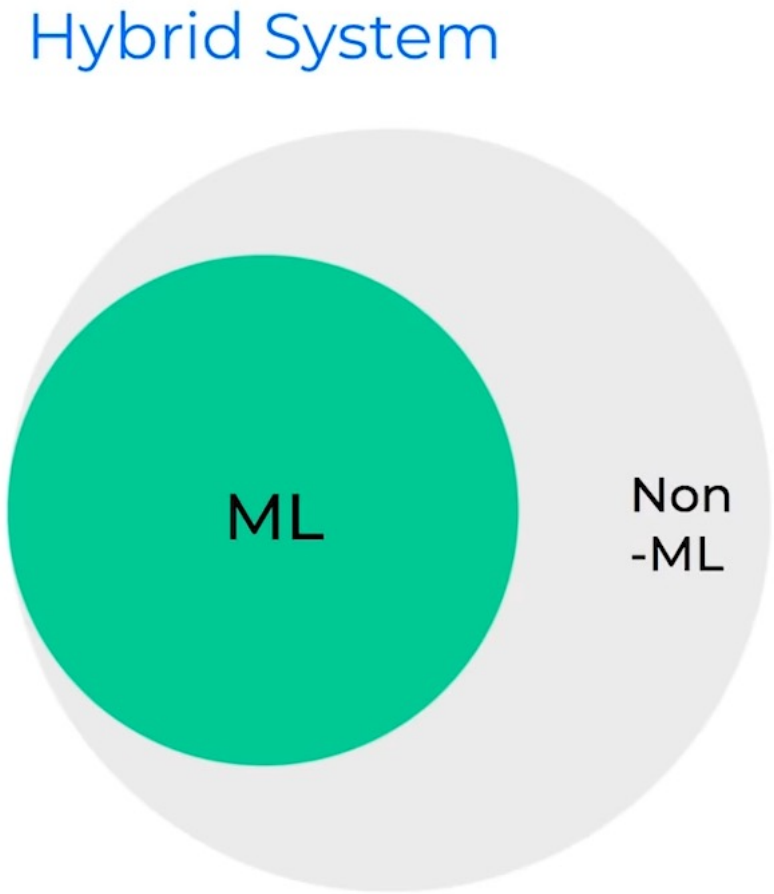
Standards and Regulations (Cont.'d)

Standart Kodu	L0 ve L1 ISO Standartları
ISO 15623:2013	Intelligent transport systems — Forward vehicle collision warning systems —Performance requirements and test procedures
ISO 19237:2017	Intelligent transport systems — Pedestrian detection and collision mitigation systems (PDCMS) — Performance requirements and test procedures
ISO 11270:2014	Intelligent transport systems — Lane keeping assistance systems (LKAS) —Performance requirements and test procedures
ISO 15622:2018	Intelligent transport systems — Adaptive cruise control systems — Performancerequirements and test procedures
ISO 17361:2017	Intelligent transport systems — Lane departure warning systems —Performance requirements and test procedures
ISO 22839:2013	Intelligent transport systems — Forward vehicle collision mitigation systems —Operation, performance, and verification requirements
ISO 22078:2020	Intelligent transport systems — Bicyclist detection and collision mitigation systems (BDCMS) — Performance requirements and test procedures
Standart Kodu	**L2 ve Sonrası ISO Standartları**
ISO 17387:2008	Intelligent transport systems — Lane change decision aid systems (LCDAS) —Performance requirements and test procedures
ISO 21202:2020	Intelligent transport systems — Partially automated lane change systems(PALS) — Functional / operational requirements and test procedures
ISO 21717:2018	Intelligent transport systems — Partially Automated In-Lane Driving Systems(PADS) — Performance requirements and test procedures
ISO/DIS 22737	Intelligent transport systems — Low-speed automated driving (LSAD) systems for predefined routes — Performance requirements, system requirements and performance test procedures
ISO 16787:2017	Intelligent transport systems — Assisted parking system (APS) — Performance requirements and test procedures
ISO 20900:2019	Intelligent transport systems — Partially automated parking systems (PAPS) —Performance requirements and test procedures
ISO 22840:2010	Intelligent transport systems — Devices to aid reverse manoeuvres — Extended-range backing aid systems (ERBA)
ISO 17386:2010	Transport information and control systems — Manoeuvring Aids for Low Speed Operation (MALSO) — Performance requirements and test procedures
Standart Kodu	**SAE Standartları**
J3157_201902	Active Safety Bicyclist Test Targets Recommendation
J3116_201706	Active Safety Pedestrian Test Mannequin Recommendation
J2802_201506	Blind Spot Monitoring System (BSMS): Operating Characteristics and User Interface
J2399_201409	Adaptive Cruise Control (ACC) Operating Characteristics and User Interface
J2400_200308	Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements

Datasets

- https://www.nuscenes.org/
  - Over 1M 3D objects
- https://github.com/waymo-research/waymo-open-dataset
  - 12M labeled 3D LiDAR objects, around 113k unique LiDAR tracking IDs, around 12M labeled 2D image objects and around 254k unique image tracking IDs.
- https://level-5.global/data/ (Lyft Level 5 Dataset)
- Berkeley Deep Drive, City Scapes, KITTI, Semantic-KITTI

ML and Non-ML Hybrid Systems



When deep neural net outputs are not *confident* or *consistent*, leverage ***expert domain knowledge***:

- **Simpler input representations with built-in bias** can generalize better with little data
- **Expert-designed algorithms**

Drago Anguelov (Waymo) - MIT Self-Driving Cars : https://youtu.be/Q0nGo2-y0xY

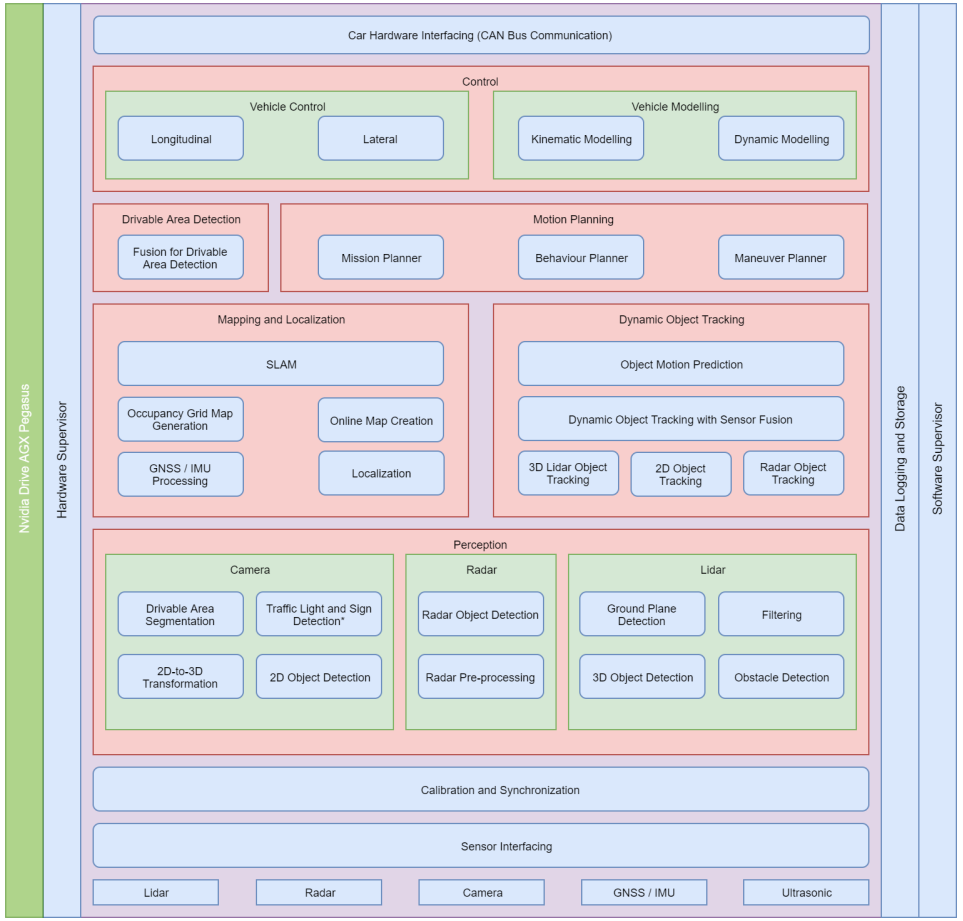
KUARTIS Develops Universal Autonomy for Wide Range of Ground Vehicles (On-Road/Off-Road)

UNIVERSAL AUTONOMY

- Operational in GPS-denied settings
- Advanced perception for L3+ autonomous driving
- Operational w/o HD-Map in conditional situations
- Realistic simulation for fast and reliable software development
- Operational in harsh environments through sensor fusion
- Advanced perception for non-ideal road conditions
- Advanced planning and control

KILAVUZ: AI-Based Technology Stack

- Sensor Fusion
- Simultaneous Localization and Mapping
- Deep Learning-based Perception
- Deterministic Perception
- Tracking and Motion Prediction
- Robotic Control and Planning
- Calibration and Synchronization



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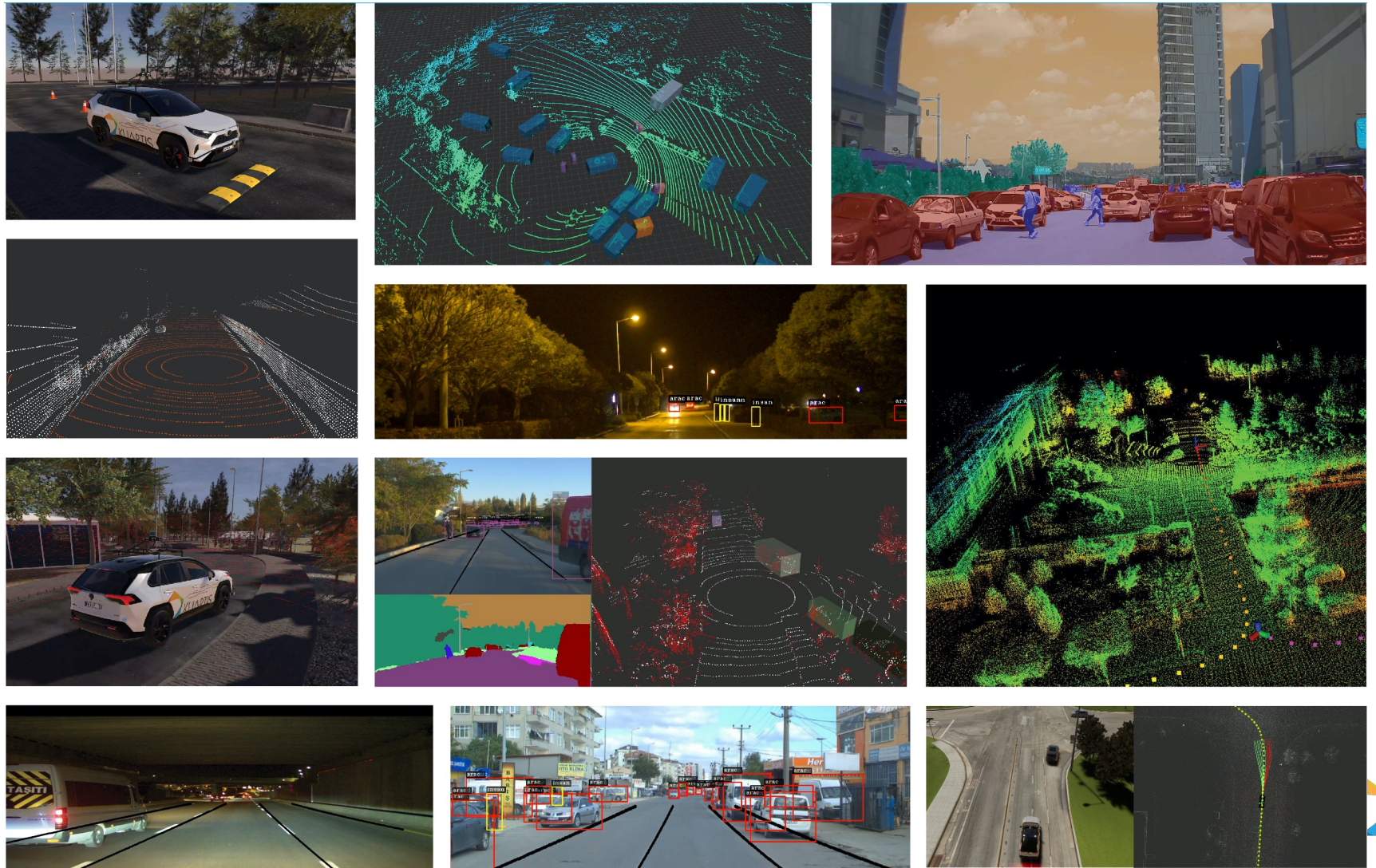
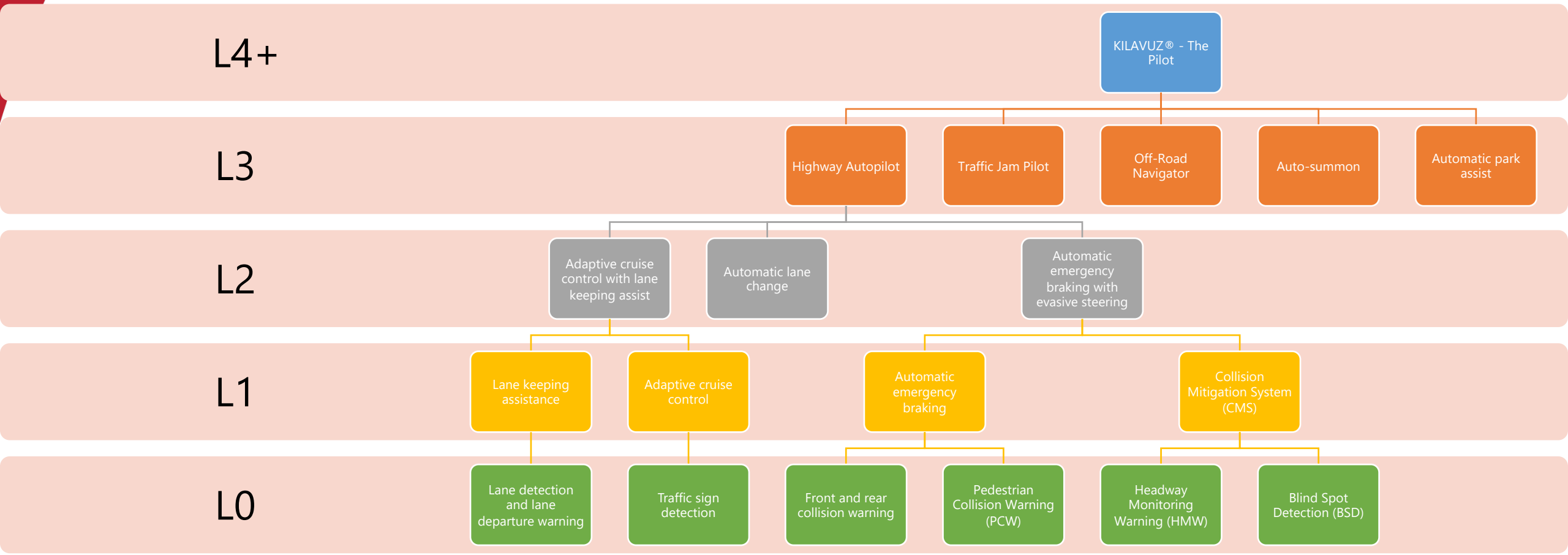
KILAVUZ: AI-Based Technology Stack



KUARTIS

A Unified Product Family (Simplified)



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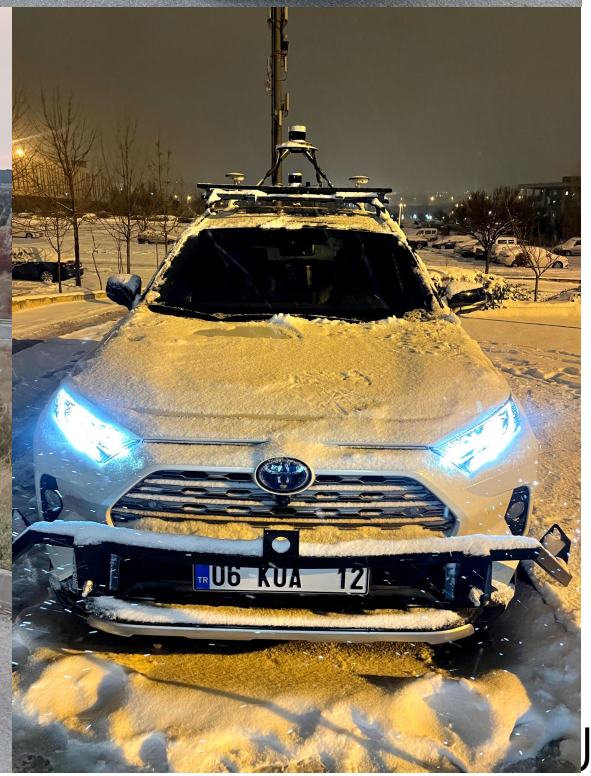
Our Current Test Vehicle



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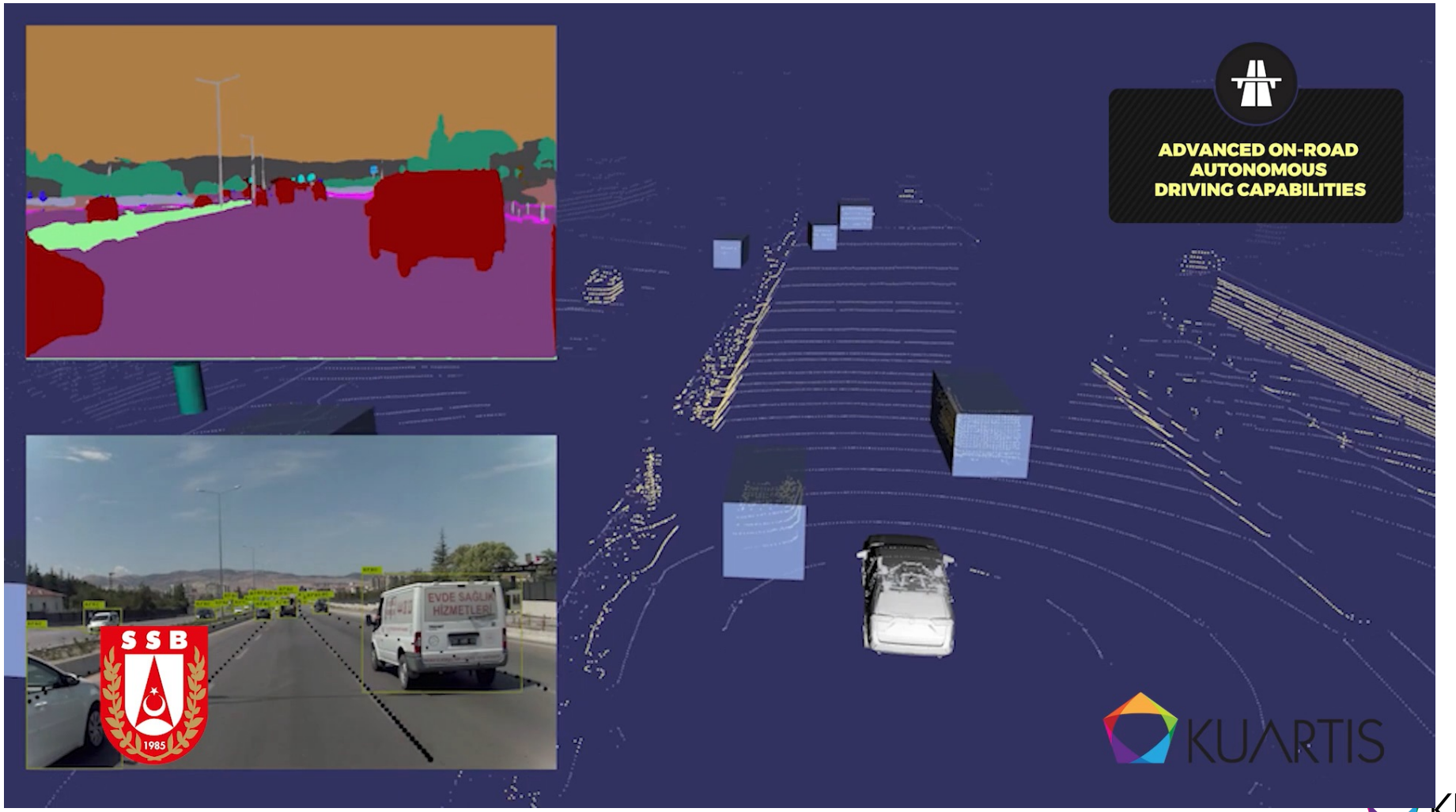
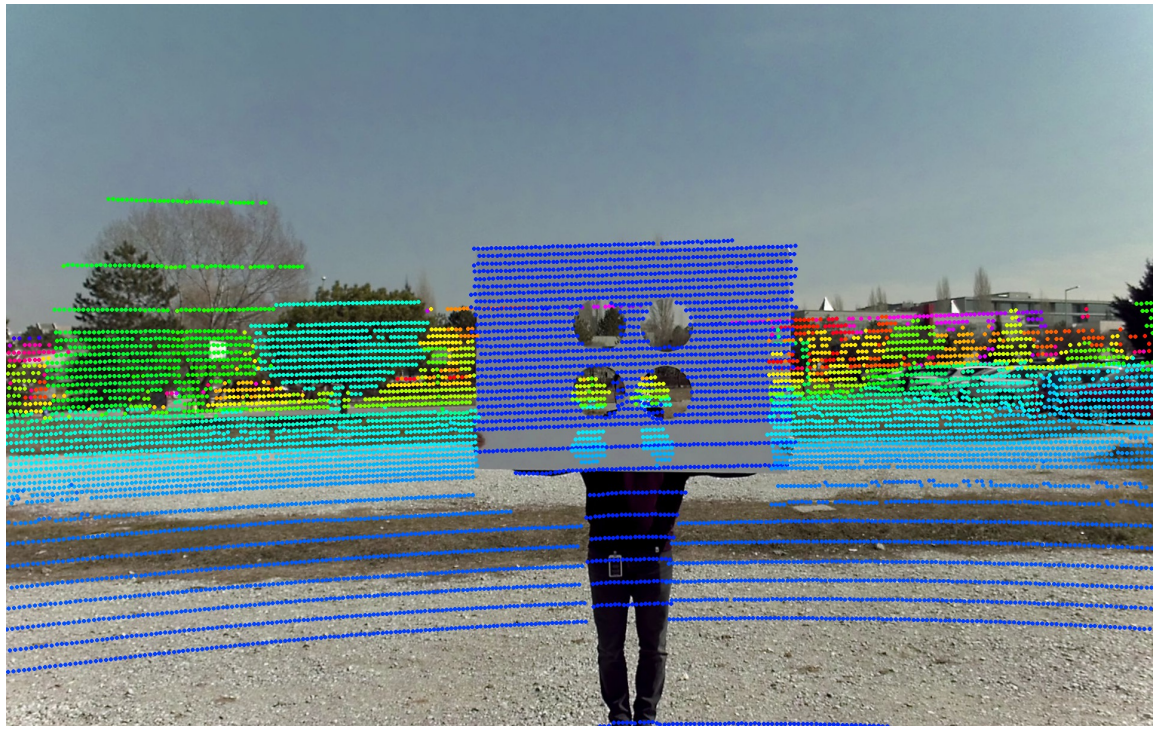
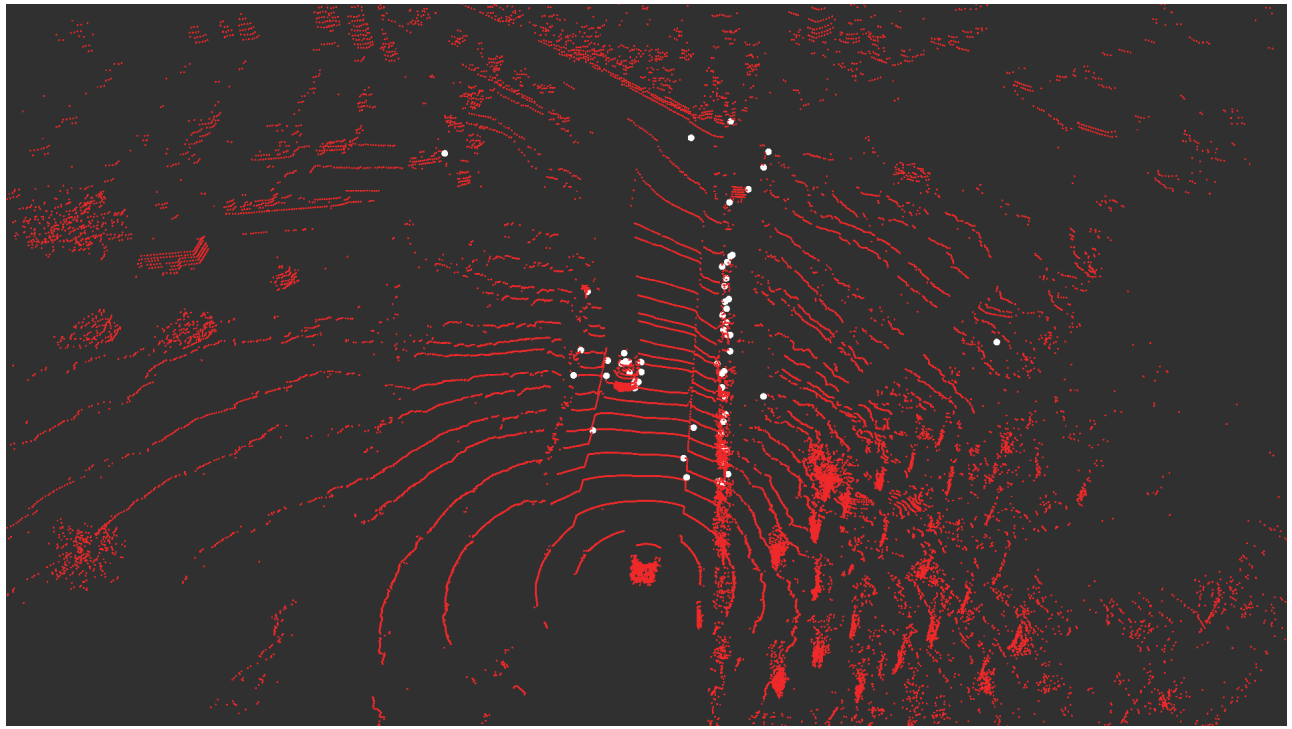
Kuartis - Demonstration



Calibration





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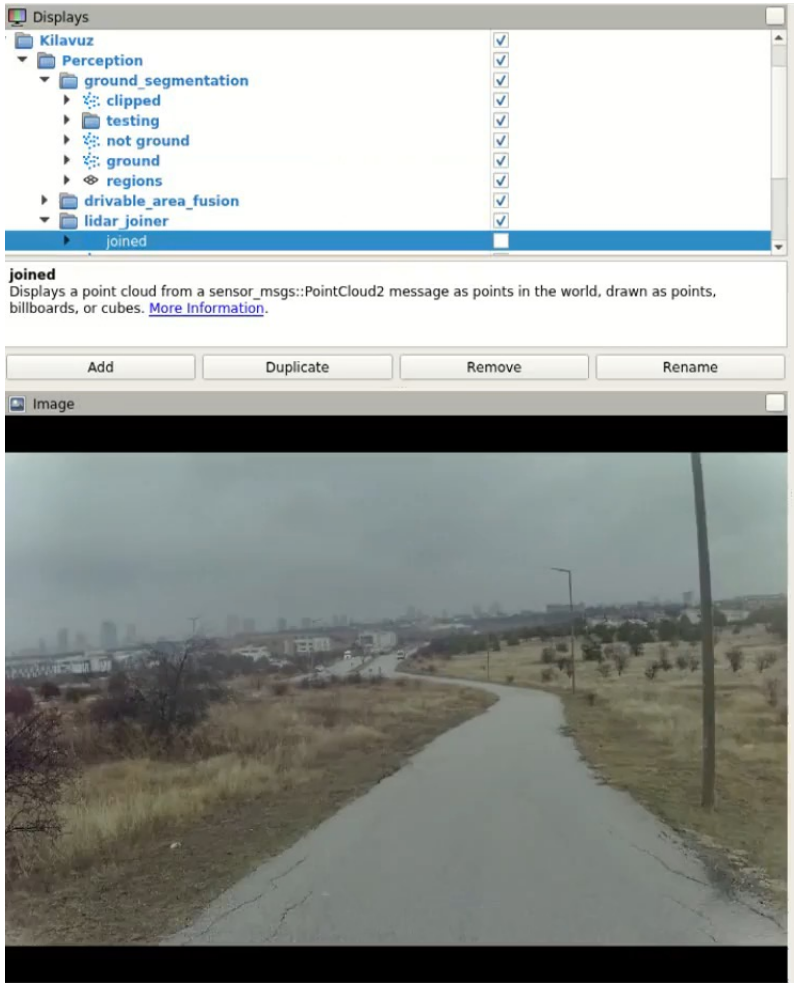
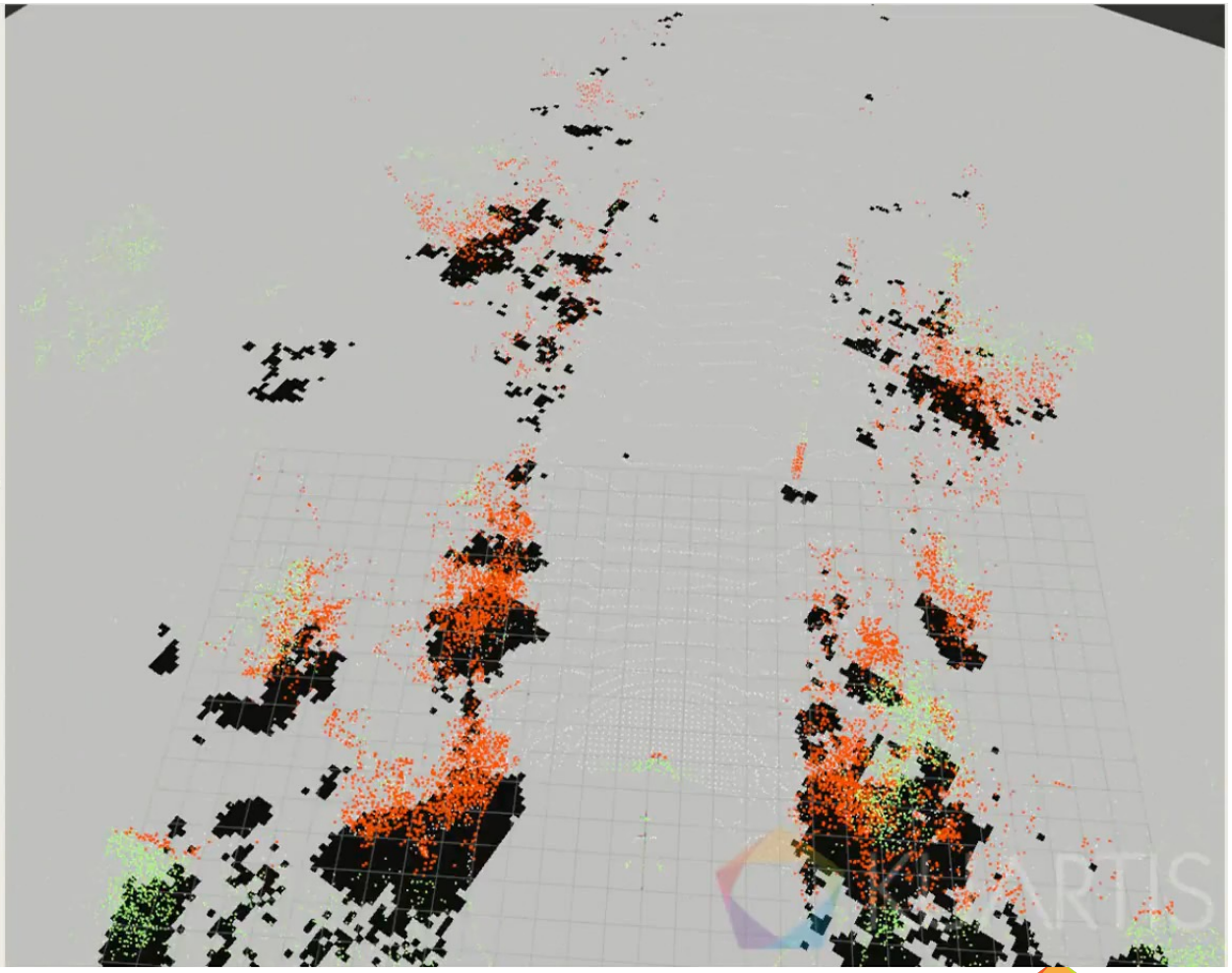
Kuartis - Deterministic Obstacle Detection





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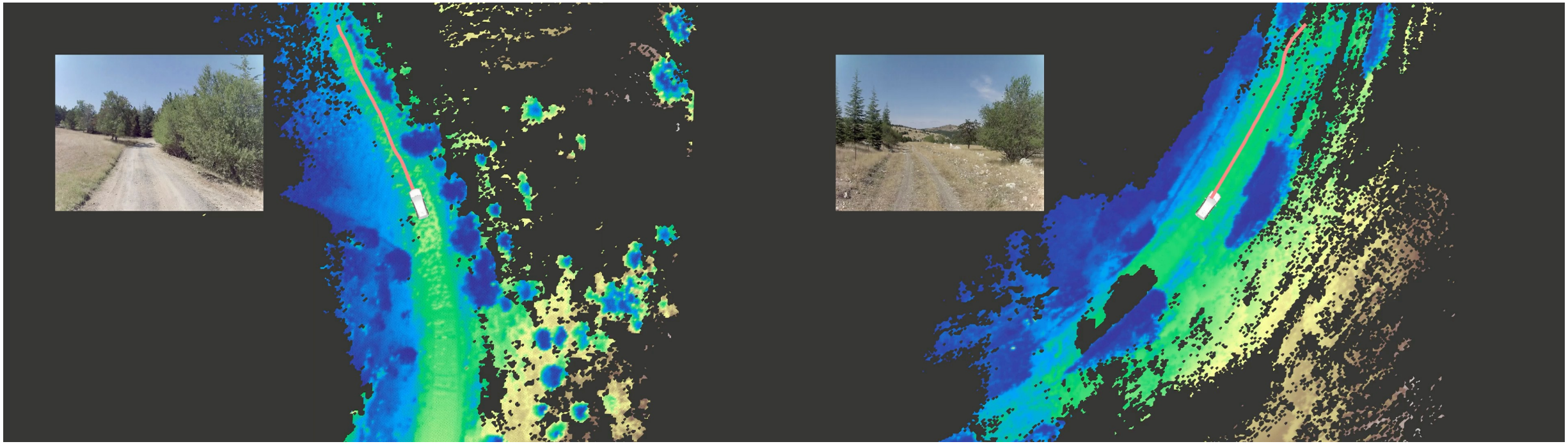
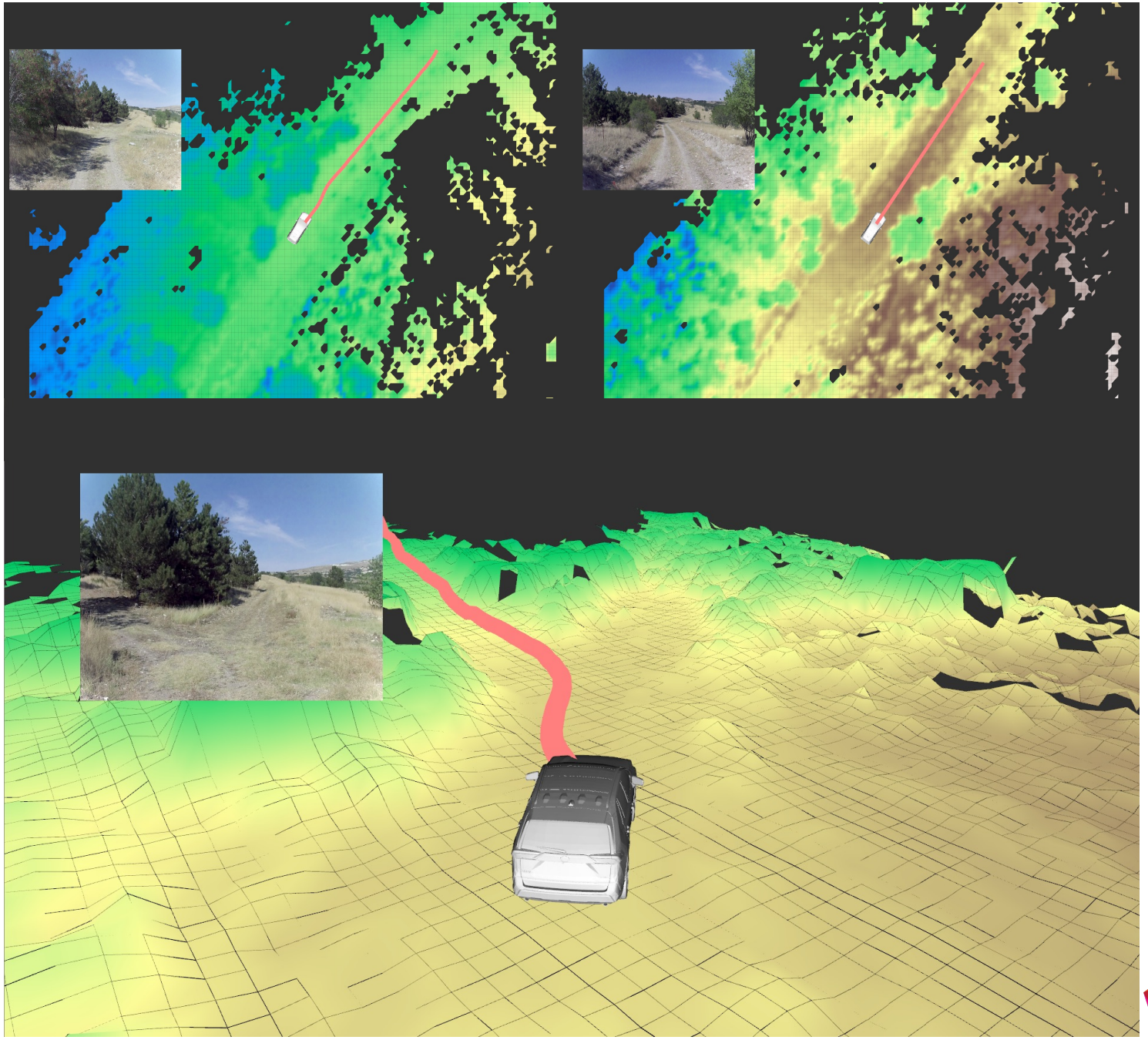
Kuartis - Off-Road Navigator



KUARTIS

Kuartis - Off-Road Navigator



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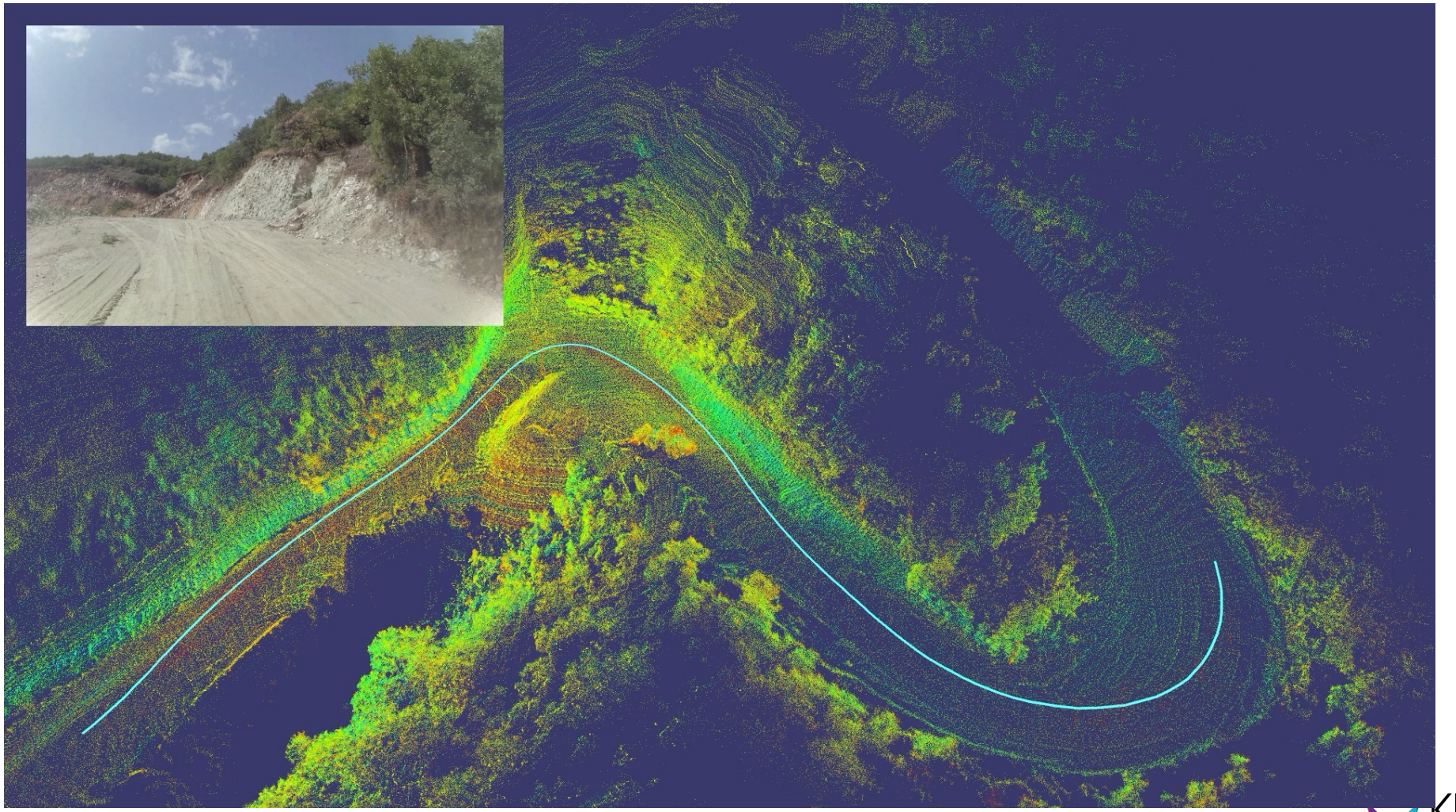
Kuartis - SLAM



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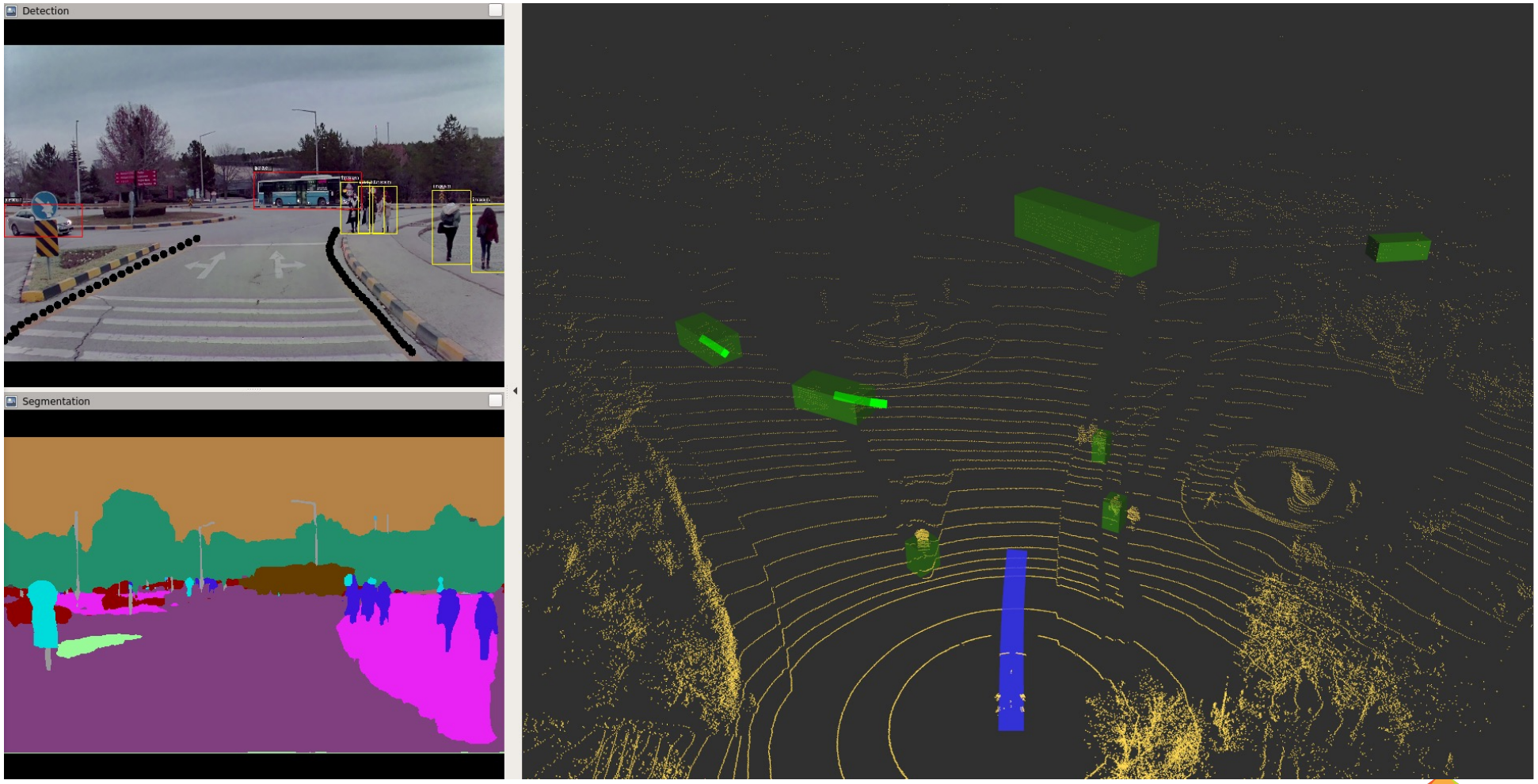
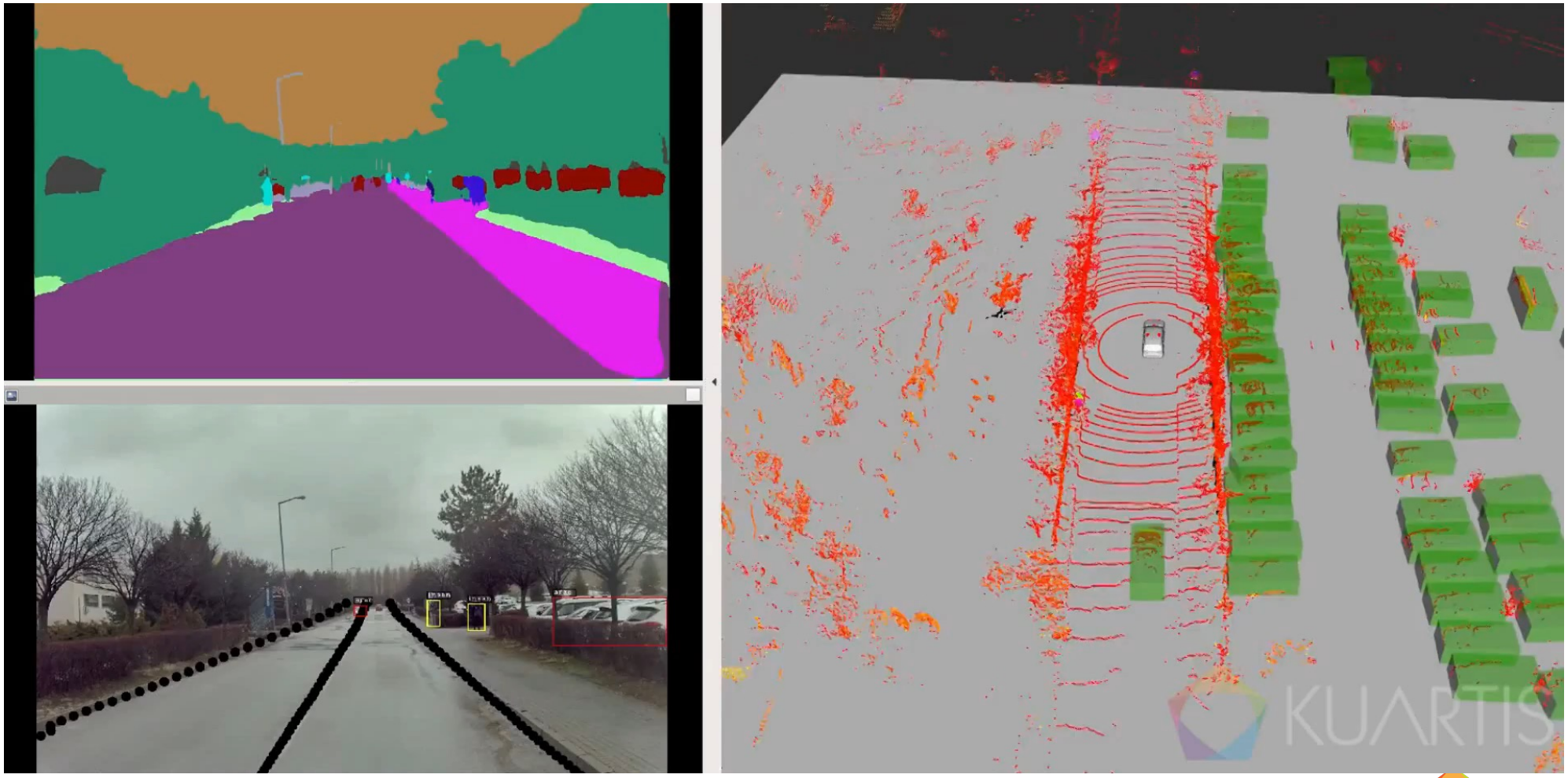
Kuartis - Sensor Fusion



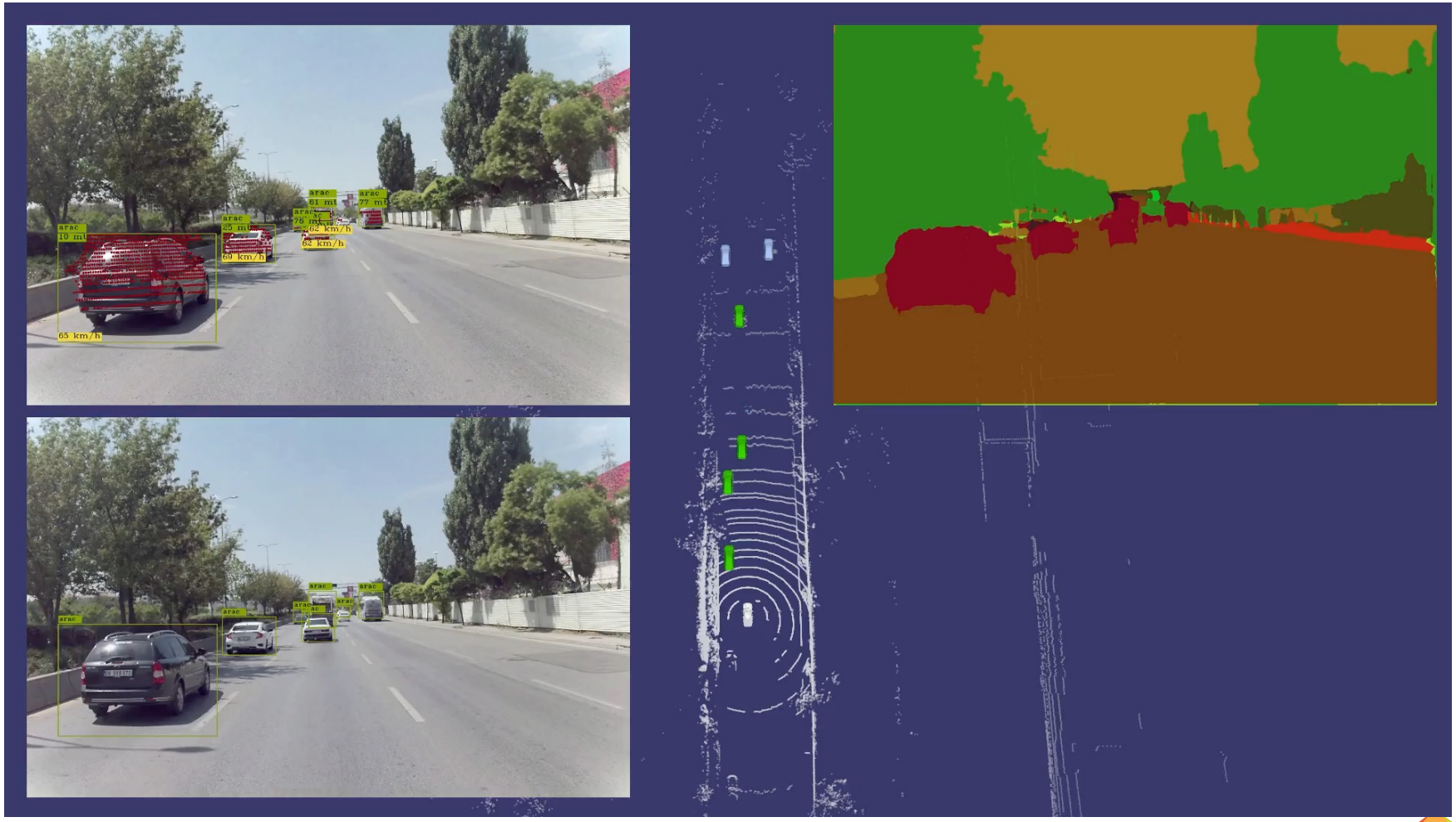
KUARTIS

Kuartis - Sensor Fusion



KUARTIS

Kuartis - Sensor Fusion



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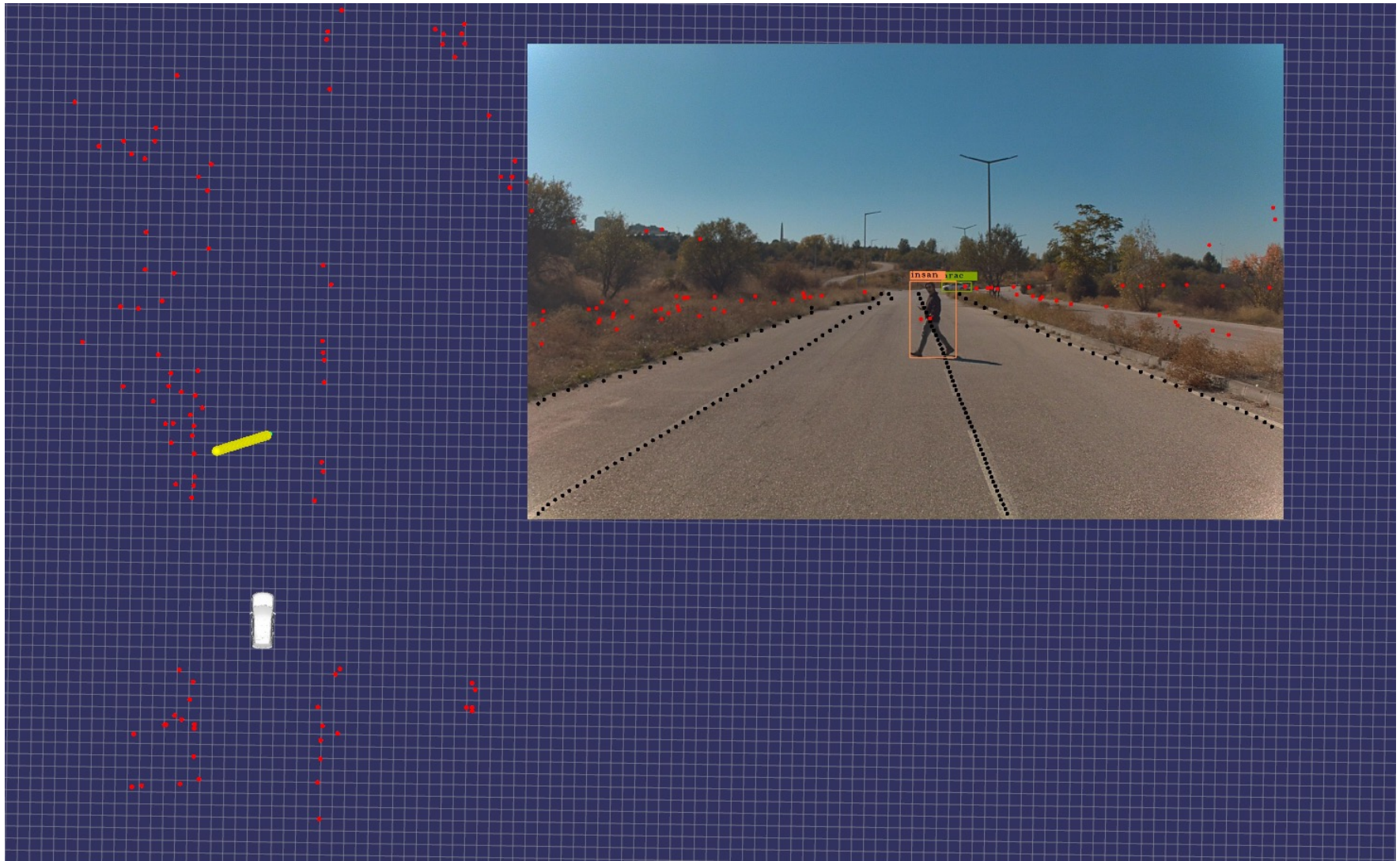
KUARTIS - ADAS

Example KUARTIS – ADAS solution that fuses RADAR and camera for lane and obstacle detection.
- Red dots are RADAR points
- Black dots are lanes



KUARTIS - ADAS

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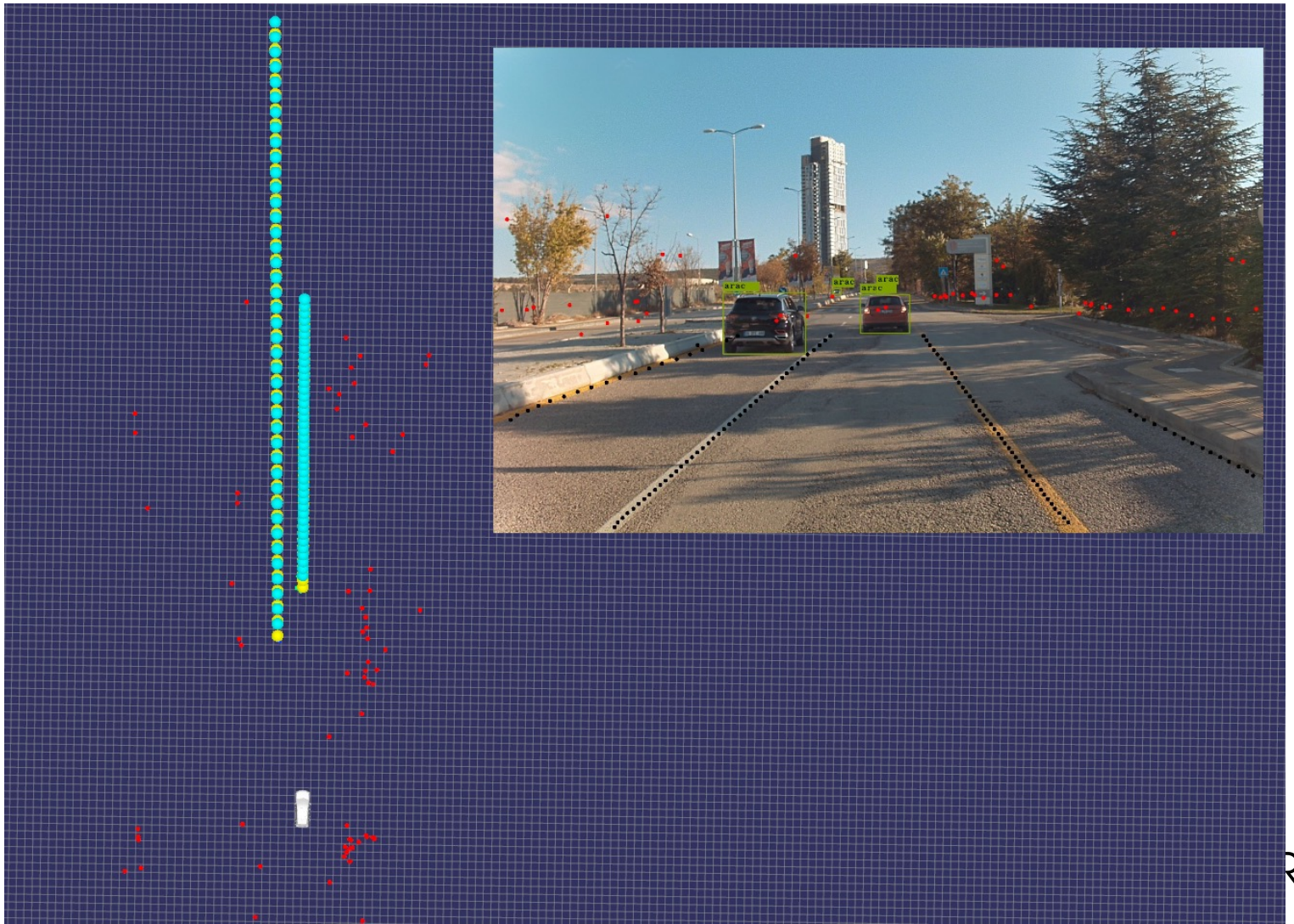
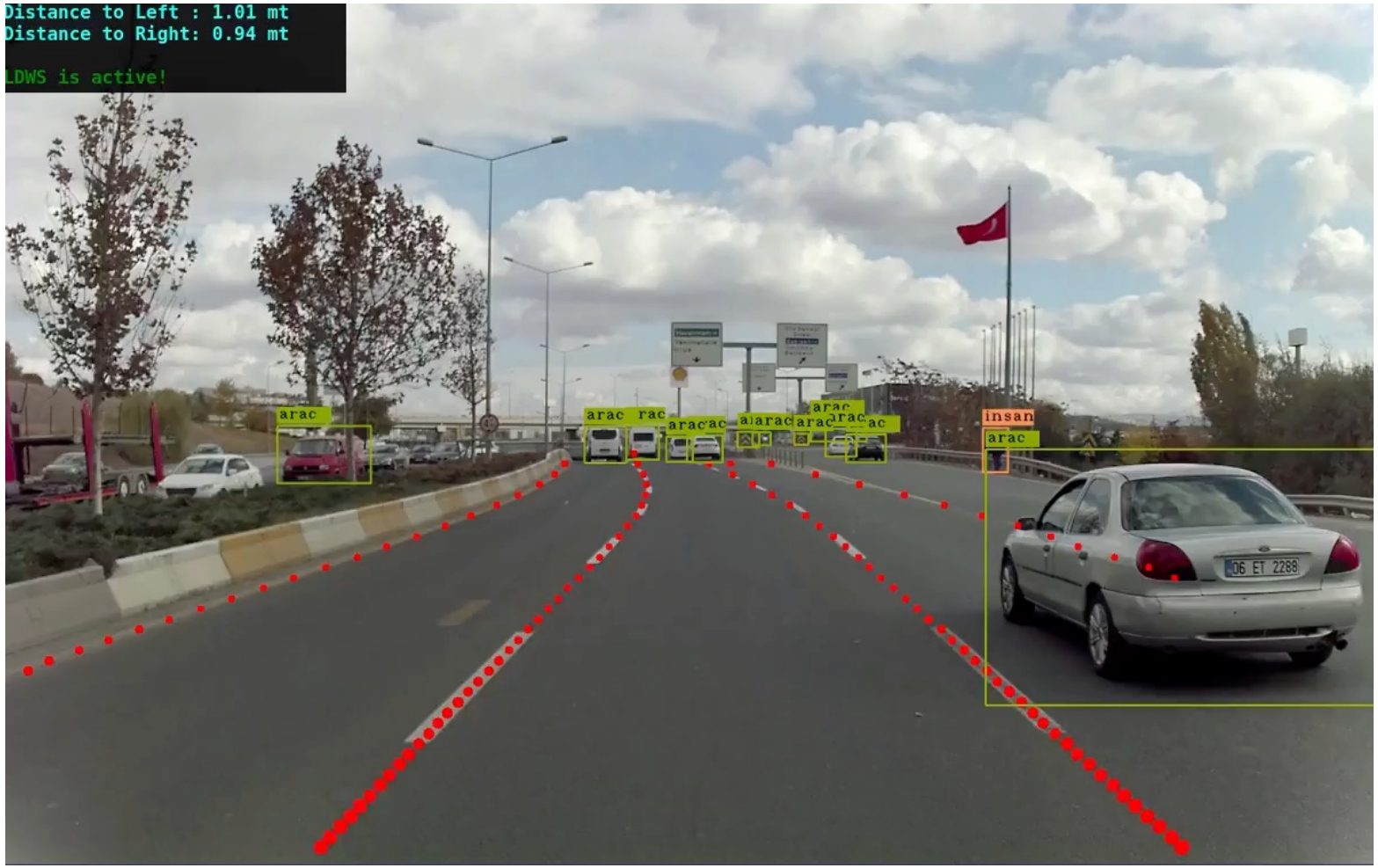


Kuartis - Sample Application: LDWS w/ Single Camera



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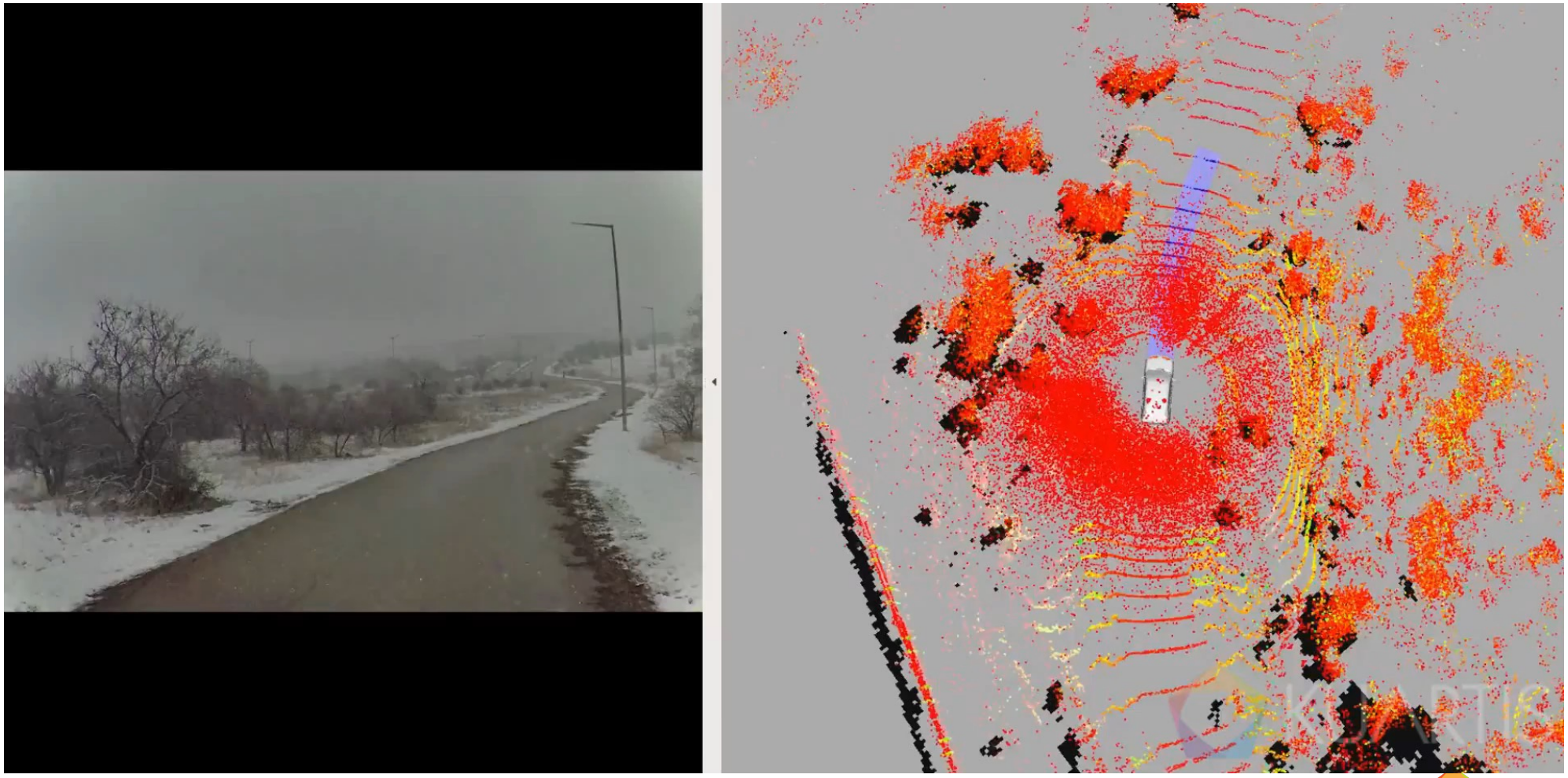
Day/Night?

KUARTIS

All Weather?



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Kuartis- Simulation

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