

Robotics

Erwin M. Bakker | LIACS Media Lab



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Organization and Overview

Lecturer:

Dr Erwin M. Bakker (erwin@liacs.nl)
Room LIACS Media Lab (LML)
Please email for a meeting.

Period: February 11th - May 13th 2025

Time: Tuesday 11.15 - 13.00

Place (Rooms): Van Steenis F1.04

Exceptions:

Gorlaeus Building BM.1.33 on April 1st
Gorlaeus Building BM.1.23 on May 20th

Teaching assistants:

TBA

Schedule (tentative, visit regularly):

Date	Subject
11-2	Introduction and Overview
18-2	Locomotion and Inverse Kinematics
25-2	Robotics Sensors and Image Processing
4-3	SI AM + Workshop@Home
11-3	Robotics Vision + Introduction Mobile Robot Challenge
18-3	Project Proposals I (by students)
25-3	Project Proposals II (by students)
1-4	Robotics Reinforcement Learning + RL Workshop@Home
8-4	Project Progress Reports I
15-4	Project Progress Reports II
22-4	Mobile Robot Challenge I
29-4	Mobile Robot Challenge II
6-5	TBA
13-5	Project Demos I
20-5	Project Demos II
27-5	Project Deliverables



Grading (6 ECTS):

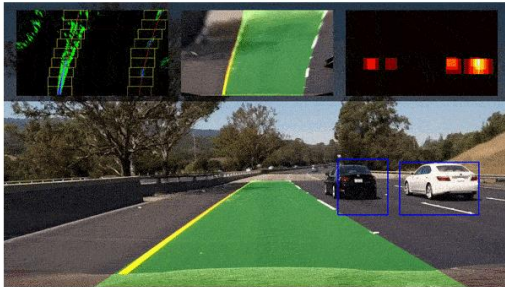
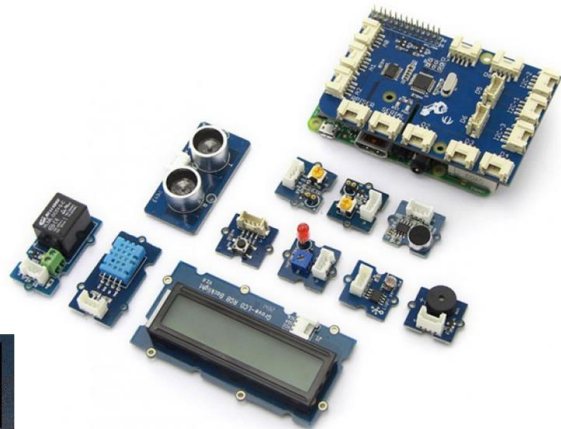
- Presentations and Robotics Project (60% of grade).
- Class discussions, attendance, 2 assignments (pass/no pass)
- 2 Workshops (0-10) (20% of the grade).
- Mobile Robot Challenge (0-10) (20% of the grade)
- ***It is necessary to be at every class and to complete every workshop and assignment.***

Website: <http://liacs.leidenuniv.nl/~bakkerem2/robotics/>

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Overview

- Sensors
- Lane Tracking
- OpenCV
- Line/Lane Tracking



IMPORTANT

- Project Groups and Proposals
- Groups Mobile Robot Challenge

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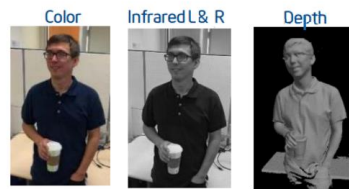
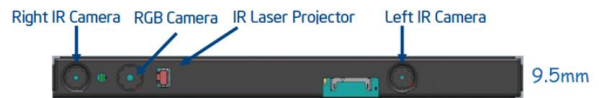
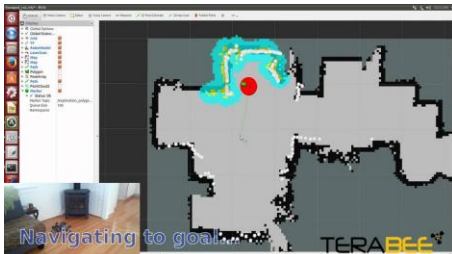
ROBOTICS SENSORS

- Bumper switches
- Acceleration, Orientation, Magnetic
- IR/Visible Light
- Pressure, Force
- Ultrasonic, Lidar, Radar
- Camera's, stereo camera's
- Structured Light Camera's

The perfect anti-collision solution for any environment

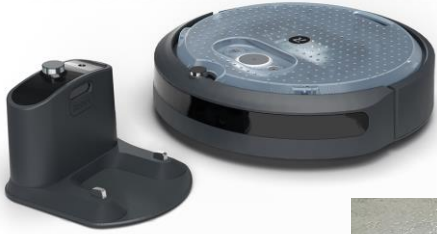
Technology Comparison
Distance sensors for robotics

	Ultrasonic	Infrared Triangulation	Laser	TeraBee (stereo IR)
High reading frequency	✗	✗	✓	✓
Long range	✗	✗	✓	✓
Minimal weight	✓	✓	✗	✓
Small form factor	✓	✓	✗	✓
Eye safety	✓	✓	Class 1, laser only	✓
Use with multiple sensors	✗	✗	✗	✓



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IROBOT CREATE 3



Sensors

- 1x Power button 2x User buttons
- 2x Front bumper zones
- 2x Wheel encoders
- 4x IR cliff sensors
- 7x IR obstacle sensors
- 1x Downward optical flow sensor for odometry
- 1x 3D gyroscope
- 1x 3D accelerometer
- 1x Battery level monitor



Technical Details

- 14.29 cm x 40.64 cm x 47.31 cm, 4.68 kg

Connectivity

- Wi-Fi or Ethernet over USB Host: Connect and control the robot using ROS 2.
- Bluetooth® Low Energy: Connect to and control the robot using [iRobot Education's Python Web Playground](#).

Battery

- 1800 mAh Li-Ion rechargeable battery

Actuators

- 2x Drive motors
- 6x RGB LED ring
- 1x Speaker

Charging and Expansion

- 1x Docking port
- 1x USB-C™ port, 3A at regulated 5V
- 1x Payload power, 2A at unregulated (nominal 14.4V)

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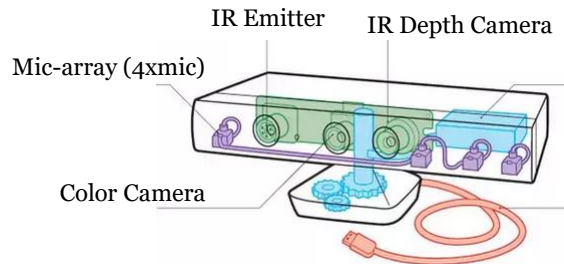
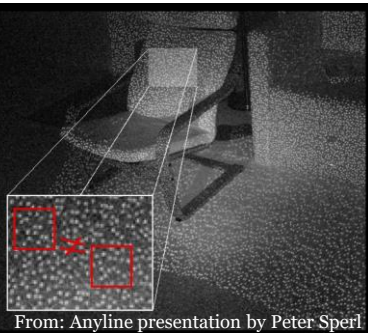
Structured Light



1. Leap Motion
2. Asus X-tion Pro Live, Microsoft Kinect v1, v2
3. Intel RealSense F200, R200 (blue), L515 (TOF)
4. ORBBEC RGB-D: Stereo, TOF, Structured Light
5. Luxonis: OAK-D line: Stereo, Structured Light

Coded Light

- Light is distorted on the surface
- Pattern is **unique** in every position on the scene
- Allows to compute depth information through triangulation

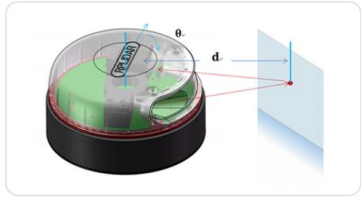


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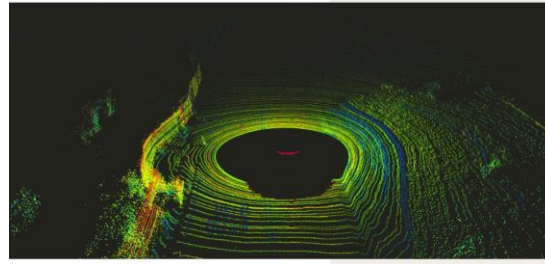
LIDAR Explanation

Traditional algorithm

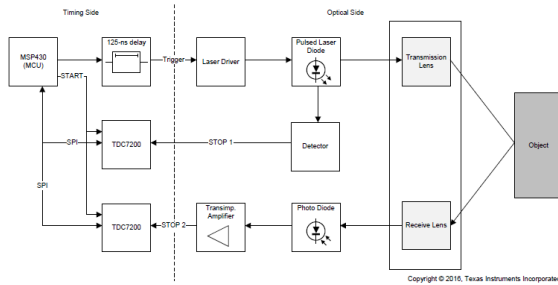
RPVision 3.0



<http://www.slamtec.com/en/lidar/A3>

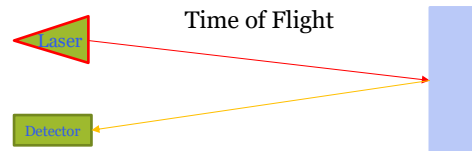


<https://news.voyage.auto/an-introduction-to-lidar-the-key-self-driving-car-sensor-a7e405590cff>



Copyright © 2016, Texas Instruments Incorporated

Texas Instruments LIDAR Pulsed Reference Design



- Speed of light $\sim 3 \times 10^8$ m/s
- In 1 picosecond ($= 10^{-12}$ sec) light travels $\sim 3 \times 10^{-4}$ m = 0.3 mm
- During 33 picoseconds light travels ~ 1 cm

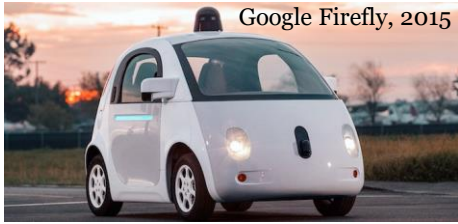


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Robotics Self Driving Cars



HOW UBER'S FIRST SELF-DRIVING CAR WORKS

Top mounted LIDAR beams 1.4 million laser points per second to create a 3D map of the car's surroundings.

There are 20 cameras looking for braking vehicles, pedestrians, and other obstacles.

A colored camera puts LIDAR map into color so the car can see traffic light changes.

Antennae on the roof rack let the car position itself via GPS.

LIDAR modules on the front, rear, and sides help detect obstacles in blind spots.

A cooling system in the car makes sure everything runs without overheating.

Ended in Dec. 2020 -> Aurora Innovation: Aurora Driver

SOURCE: Uber BUSINESS INSIDER

HOW WAYMO'S SELF-DRIVING CAR WORKS

One of Waymo's three lidar systems that shoots lasers so the car can see its surroundings. Waymo says this lidar can detect a helmet two-football fields away.

A forward facing camera works with 8 others stationed around the car to provide 360 degrees of vision.

Radar sensors can detect objects in rain, fog, or snow.

Waymo's self-driving sensors are tightly integrated into the hybrid minivan created by Fiat Chrysler.

<https://waymo.com/tech/Waymo, 2017 ->

SOURCE: Waymo BUSINESS INSIDER

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CES2019

BMW Self Driving Car

InnovizOne Solid-state Lidar (goal: sub \$1000 sensor)

- Angular resolution 0.1° x 0.1°
- FOV 120° x 25°
- 25 FPS
- Range 250m



Perception Capabilities

- Object detection and classification
- Lane detection
- Object Tracking
- SLAM

PRODUCT HIGHLIGHTS:

- High Resolution at High FPS
- Configurable Regions of Interest
- Resilient to Sunlight and Weather Conditions
- No Gaps Between Pixels
- Equally Distributed FOV



SLAM (Simultaneous Localization And Mapping)

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INDY Autonomous Challenge (CES2021 - 2025)

<https://www.indyautonomouschallenge.com>

2024 Cars:

- 360-Degree Long Range LiDAR using 4 Luminar Iris Sensors
- Advanced 4D Radar Perception using Continental ARS540 Sensors
- Improved GPS/GNSS for Enhanced Localization
- Key: Software stack, drive by wire, robustness (AI, Twin simulations, etc.)

➤ 190 mph

2025:

Multicar (4) race



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INDY Autonomous Challenge (CES2021 - 2025)

<https://www.indyautonomouschallenge.com/racecar>



LIDAR (4)

- » Luminar Iris
- » Maximum range: 275m
- » Range precision: <2cm
- » FoV: Horizontal 120° | Vertical 26°
- » Scan rate: 30 fps

RADAR (2)

- » Continental ARS 548 RDI
- » Maximum Range: 300m-1500m
- » FoV: 120°

Camera (6)

- » Allied Vision Mako G-319C / Edmund Optics Lenses
- » Max resolution: 2064 (H) x 1544 (V)
- » Spectral range: 300-1100 nm
- » Max frame rate @ full res: 37.6 fps

GNSS / INS System

- » VectorNav VN-310
- » Position Accuracy: 1 cm + 1 ppm RMS
- » Heading Accuracy: 0.1 deg
- » Position Data Rate: 400 Hz
- » IMU Data Rate: 800 Hz
- » Callan GPS Antennas (4)

Networking / Communication

- » Cisco IE-3300
- » Ports: 2x 10G
- » Switching bandwidth: 128 Gbps
- » Marelli SA130 Telemetry System
- » AVI LTE 9111 Modem
- » Verizon 4G Cellular Network

Onboard Edge Computing

- » dSPACE AUTERA AutoBox
- » CPU: Intel Xeon D-2166NT
3.00 GHz (12C, 24T)
- » GPU: Nvidia A5000
- » Storage: 14 TB

Drive-by-Wire

- » New Eagle Raptor / MathWorks
- » IAC Custom Steer-by-Wire
- » IAC Custom Brake-by-Wire
- » MoTeC ECU
- » Indy Wiring Harnesses

Engine

- » 4 Piston Racing built Honda K20C
- » Turbocharged inline 4 cylinder
- » Displacement: 2.0 liters
- » Max power: 488 hp @ 6500 RPM
- » Max torque: 382 ft-lbs @ 6100 RPM

Transmission

- » ZF anti-stall centrifugal clutch
- » Ricardo 500 Nm, 6-speed sequential

Chassis

- » Manufacturer: Dallara
- » Overall length: 192 in / 4876 mm
- » Overall width: 76 in / 1930 mm
- » Overall height: 45.5 in / 1156.5 mm
- » Wheelbase: 117 in / 2971 mm
- » Curb weight: 1680 lbs / 748.43 kg

Tires

- » Bridgestone Racing Slicks
- » Oval and Roadcourse



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Researcher Hacks Self-driving Car Sensors

\$60 lidar spoofing device generates fake cars, pedestrians and walls (2015)

By Mark Harris



Photo: Jeff Kowalski/Corbis

<https://spectrum.ieee.org/cars-that-think/transportation/self-driving/researcher-hacks-selfdriving-car-sensors>

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Illusion and Dazzle: Adversarial Optical Channel Exploits against Lidars for Automotive Applications

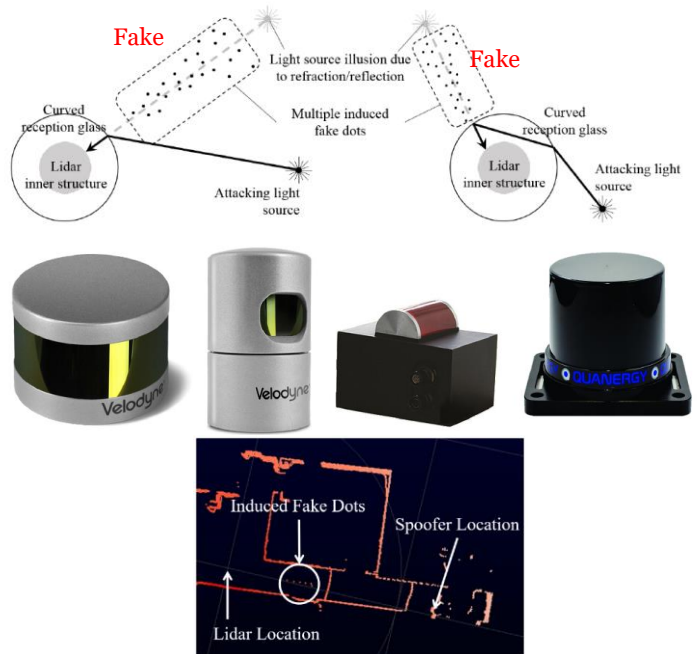
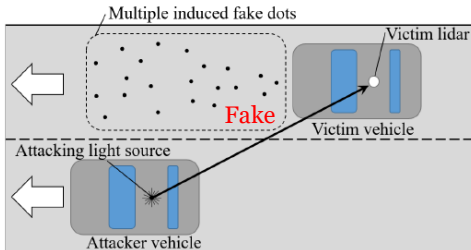
(CHES 2017)

Hocheol Shin, Dohyun Kim, Yujin Kwon, and Yongdae Kim

Korea Advanced Institute of Science and Technology, Dajeon, Republic of Korea, {h.c.shin, dohyunjk, dbwls8724, yongdaek}@kaist.ac.kr

Abstract. With the advancement in computing, sensing, and vehicle electronics, autonomous vehicles are being realized. For autonomous driving, environment perception sensors such as radars, lidars, and vision sensors play core roles as the eyes of a vehicle; therefore, their reliability cannot be compromised. In this work, we present a spoofing by relaying attack, which can not only induce illusions in the lidar output but can also cause the illusions to appear closer than the location of a spoofing device. In a recent work, the former attack is shown to be effective, but the latter one was never shown. Additionally, we present a novel saturation attack against lidars, which can completely incapacitate a lidar from sensing a certain direction. The effectiveness of both the approaches is experimentally verified against Velodyne's VLP-16.

Keywords: attack, autonomous car, sensor, lidar, saturating, spoofing



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Adversarial Sensor Attack on LiDAR-based Perception in Autonomous Driving

by Yulong Cao et al.
 CCS '19, November 11–15, 2019, London, UK.

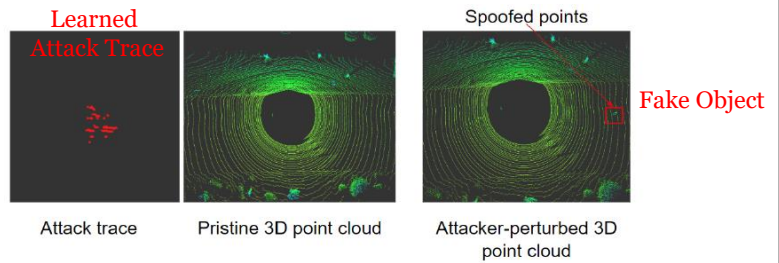
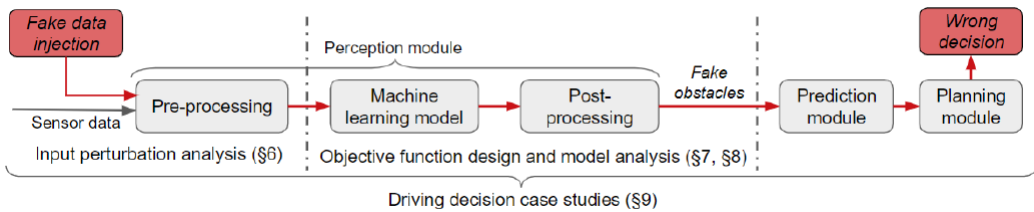
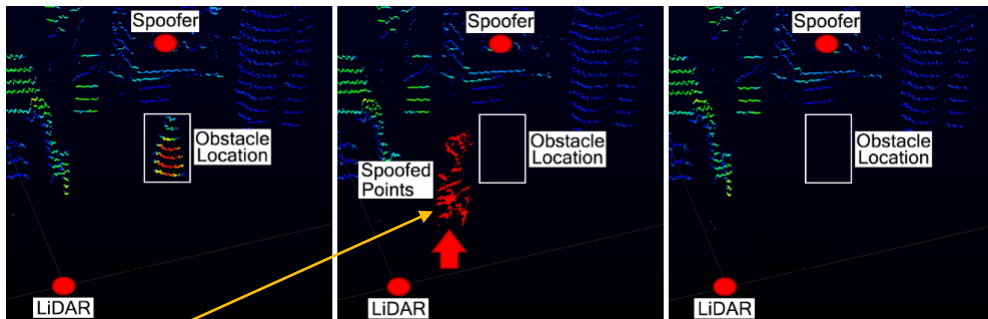


Figure 5: Generating the attacker-perturbed 3D point cloud by synthesizing the pristine 3D point cloud with the attack trace to spoof a front-near obstacle 5 meters away from the victim AV.



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Y. Cao et al. You Can't See Me: Physical **Removal Attacks** on LiDAR-based Autonomous Vehicles Driving Frameworks. 32nd USENIX Symposium, 2023.



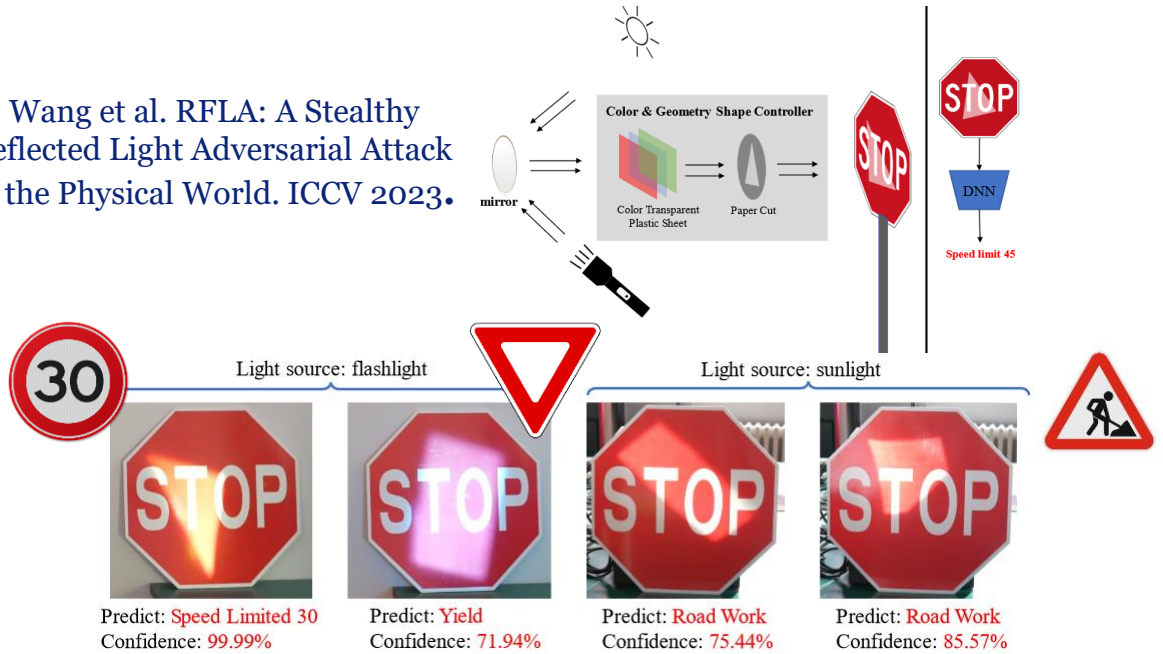
high-intensity echoes injected close to the LiDAR sensor
 ⇒ fake reflections recorded as strongest echoes
 ⇒ software ignores echoes from genuine obstacles farther away

LiDAR set up to record multiple echoes
 ⇒ spoofed points below Mean Operational Threshold (MOT)
 ⇒ can still prevent detection of obstacle

Many more studies since, also attacks against multimodal systems, e.g.,
 Y. Chao et al., *Invisible for both Camera and LiDAR: Security of Multi-Sensor Fusion based Perception in Autonomous Driving Under Physical-World Attacks*, June 2021
 Etc.

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D. Wang et al. RFLA: A Stealthy Reflected Light Adversarial Attack in the Physical World. ICCV 2023.



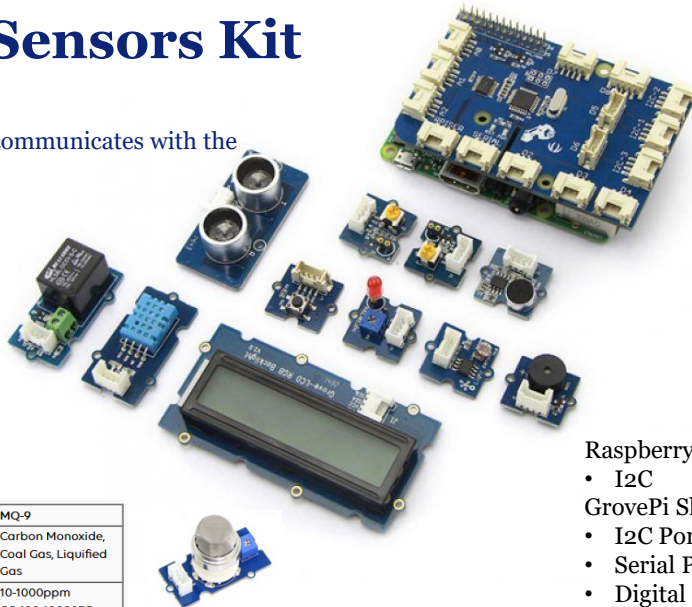
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RaspberryPi Sensors Kit

GrovePi+ Board for Raspberry Pi

De ATMEGA328 microcontroller communicates with the Raspberry Pi.

- Sound Sensor
- Temperature & Humidity
- Light Sensor
- Button
- Ultrasonic Ranger
- Rotary Angle Sensor
- Gas Sensor



Raspberry Pi -> GrovePi

- I2C
- GrovePi Shield:
 - I2C Ports
 - Serial Ports
 - Digital Ports
 - Analog Ports

Symbol	MQ-2	MQ-3	MQ-5	MQ-9
Detect Gas	Combustible Gas, Smoke	Alcohol Vapor	LPG, Natural Gas, Town Gas	Carbon Monoxide, Coal Gas, Liquefied Gas
Detect Concentration	300-10000ppm	0.04-4mg/L Alcohol	300-10000ppm	10-1000ppm CO;100-10000PPm Gas

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Unitree Go2 Pro



- Orin NX
- Voice Module (SR)
- **Navigation Lidar**
- **Radar Module**
- **Camera**
- **IMU**
- 12 DOF
- Payload ~8kg
- Speed 3.7 m/S (max 5m/s)

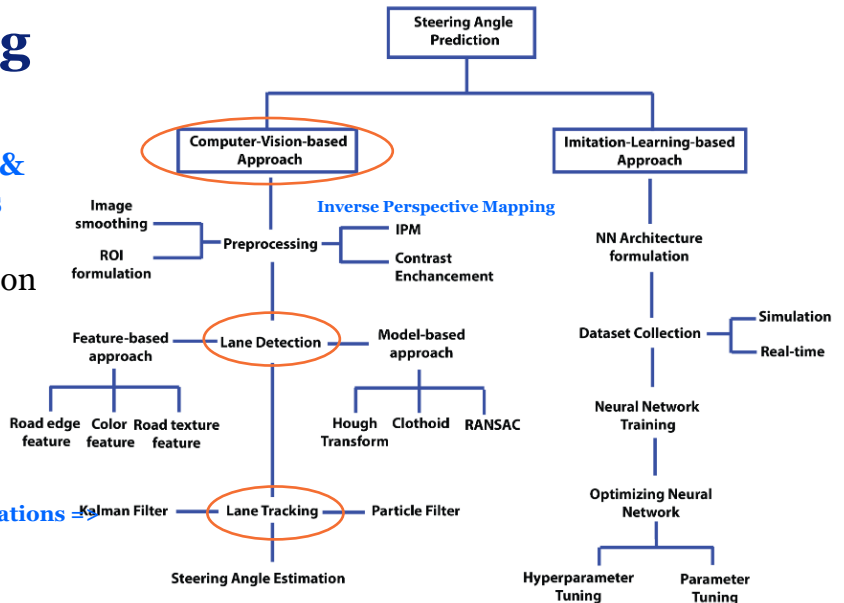
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Lane Tracking

Autonomous Driving & Driver Assist Systems

- Steering Angle Prediction
- Lane Detection
- Lane Tracking

Noisy and partial observations →



H. Saleem et al., Steering Angle Prediction Techniques for Autonomous Ground Vehicles: A Review. IEEE Access, June 2021

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Lane Tracking

- Joel C. McCall and Mohan M. Trivedi, **Video Based Lane Estimation and Tracking for Driver Assistance: Survey, System, and Evaluation**. IEEE Transactions on Intelligent Transportation Systems, 2006 (1443 citations)
- A. Bar Hillel, R. Lerner, D. Levi, G. Raz, **Recent progress in road and lane detection: a survey**. *Machine Vision and Applications* (2014) 25:727–745 (1048 citations)
- J. Fritsch, T. Kühnl, F. Kummert, **Monocular Road Terrain Detection by Combining Visual and Spatial Information**. IEEE Transactions on Intelligent Transportation Systems, 2014. (99 citations)
- J. Sattar, J. Mo, **SafeDrive: A Robust Lane Tracking System for Autonomous and Assisted Driving Under Limited Visibility**. January 31, 2017 (5 citations)
(<https://arxiv.org/abs/1701.08449>)

Some example project for detecting road features using OpenCV:
<https://navoshta.com/detecting-road-features/> by Alex Staravoitau

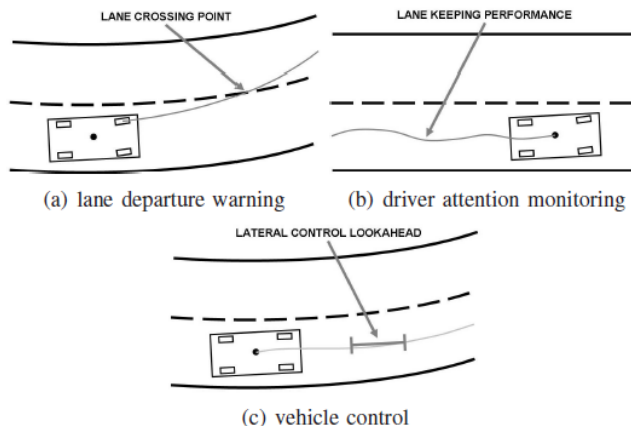
Note:

- J. Tang et al. A review of lane detection methods based on deep learning. *Pattern Recognition*, Vol 111 2021. (218 citations)
- D.-H. Lee et al. End-to-end deep learning of lane detection and path prediction for real-time autonomous driving. *Signal, Image and Video Processing*, 2023. (97 citations)

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Lane Tracking

Joel C. McCall and Mohan M. Trivedi, **Video Based Lane Estimation and Tracking for Driver Assistance: Survey, System, and Evaluation**. IEEE Transactions on Intelligent Transportation Systems, 2006 (1443 citations)



(a) A simple road with solid and segmented line lane markings (b) Circular reflectors and solid-line lane markings with non-uniform pavement texture



(c) Dark on light lane markings (d) A combination of segmented lines, circular reflectors, and physical barrier marking lane location



(e) Highly cluttered shadows from trees obscuring lane markings (f) Freeway overpass causing extreme lighting changes and reducing road marking contrast

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Lane Tracking by Day and Night

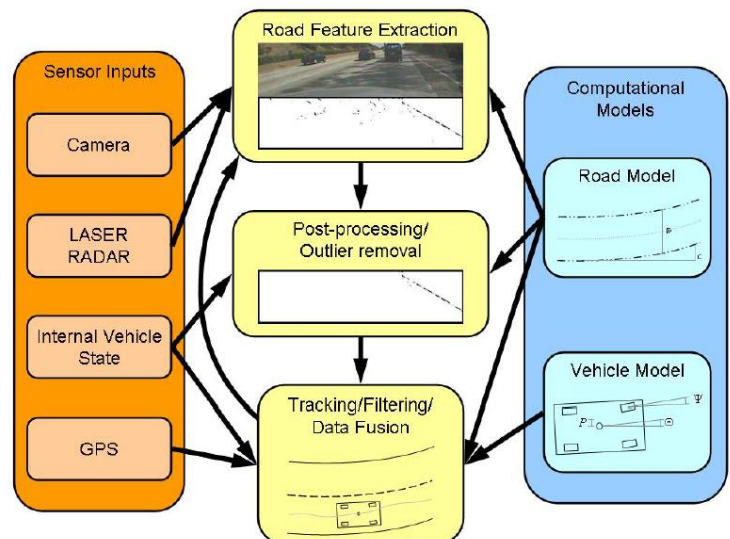


Fig. 3. Images of the same stretch of road shown in the daytime and nighttime

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General System

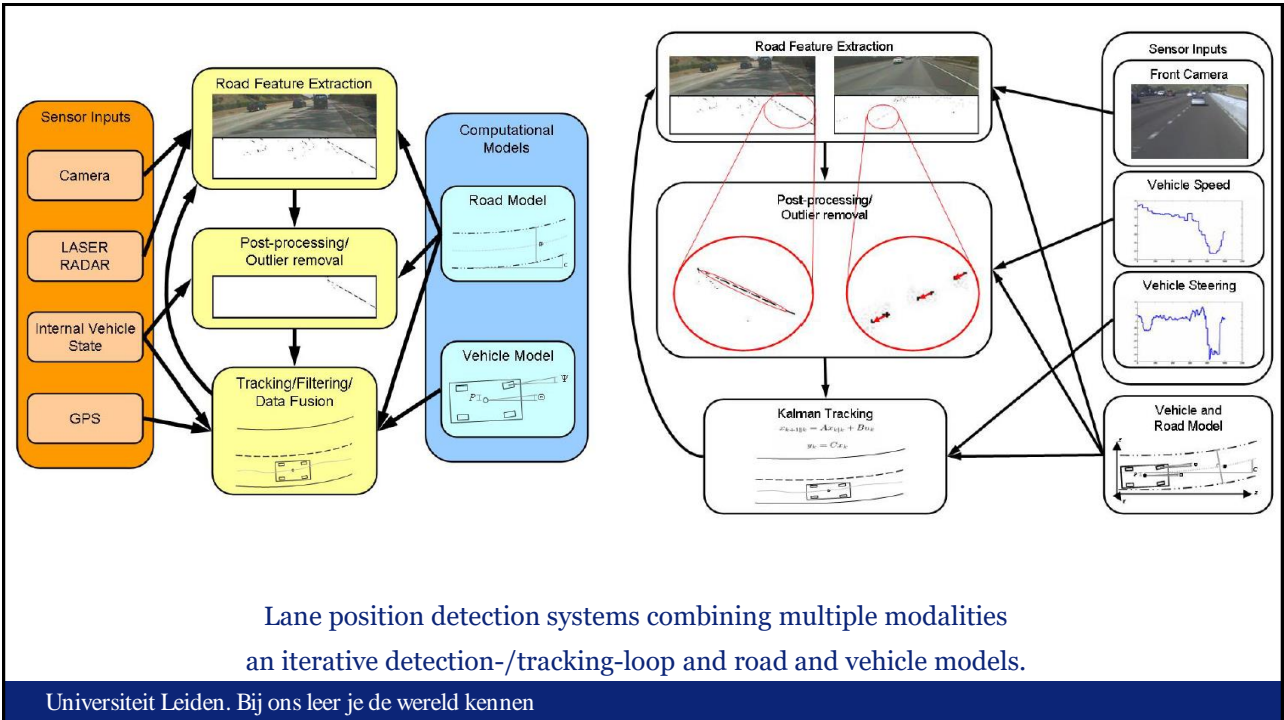
1. camera and vision sensors
2. internal vehicle state sensors
e.g., speed, steering angle, etc.
3. line detectors, etc.
4. LASER RADAR sensors
5. GPS sensors



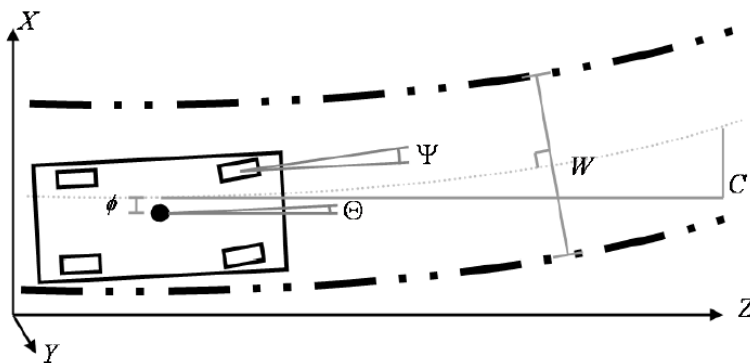
Lane position detection system (from paper):

- combining *multiple modalities*
- an iterative detection-/tracking-loop
- using road and vehicle models.

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Vehicle and Road Models



- A constant curvature road model
- Linearized vehicle dynamics
- Kalman Filter Applied

Kalman Filter: Linear Quadratic Estimation to cope with noisy data.

System	Use ²	Road Model	Feature Extraction	Postprocessing	Tracking	Evaluation	Comments
VaMoRs (1992) [16]	A	Clothoid Model with vertical curvature	Edge Elements	eliminates points which are not collinear	Linear vehicle dynamics model	Single frame images	Limited processing power. Simple edge detection fails in difficult situations.
YARF (1995) [33]	A	Circular road segments on flat plane	Hue based segmentation and edge detection	Averaging and linear median squares estimation	Operation on single frame	Positive detection rates for feature extraction, single frame images	Multiple detectors. Limited to yellow and white stripes.
ALVINN (1996) [19], [36]	A	Flat road model for generating training data	Image intensity	Neural Network	None	Road tests, various error measure associated with neural networks	Neural network makes it difficult to decouple control from detection, requires lots of training
RALPH (1996) [25]	A B	Constant curvature on flat plane	scan line matched to template	Template matching to slowly evolving near template and fast evolving far template	No inter-frame tracking described	Single frame images	template methods can fail near construction zone or areas where the road has changed. Shows limited quantitative results
GOLD (1998) [20]	C	Constant lane width on flat plane	Adaptive thresholding of pixel differences	Morphological widening	Operation on single frame	Single frame images	Assumes line markings on dark road, some robustness to lighting and occlusion
LOIS (1998) [34]	B A	Parabolic approximation on flat plane	Edge magnitudes and orientations	Maximum a posteriori estimation evaluated by Metropolis algorithm	Kalman filtering	Error histogram from one drive. Standard deviation of error 13cm	Robust to shadowing in presence of strong lane markings. Otherwise untested.
LANA (1999) [24]	B A	Parabolic approximation on flat plane	DCT coefficients for diagonally dominant edges	Maximum a posteriori estimation	Operation on single frame	Single frame images, comparison to LOIS shown	Only using diagonal DCT coefficients limits detection based on orientation of vehicle
Taylor et al. (1999) [12]	A	Constant curvature on flat plane	Template matching	Hough transform	Kalman Filter input into various control schemes	Performance of controllers shown	Focused on controller performance. Limited real-world testing.
Ma et al. (2000) [13]	A B C	Circular road model on flat plane	Likelihood based on gradient image	Fusion on radar and optical images	Operation on single frame	Single frame images	Designed for elevated or bordered rural roads.

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System	Use ²	Road Model	Feature Extraction	Postprocessing	Tracking	Evaluation	Comments
Southall et al. (2001) [30]	C	Curvature and rate of change of curvature	Threshold both pixel values and cross-correlation to dark-bright-dark function	Factored sampling for particle filter	Particle Filtering via CONDENSATION	Estimates shown for an image sequence, no ground truth or quantitative results	Very limited results and testing. Unclear whether feature extraction will work in difficult situations.
Kwon and Lee (2002) [4], [31]	B	Piecewise linear	multiple "feature transformation modules"	combined with data fusion and constraint satisfaction, heuristic departure warning function	nonlinear filtering	analysis of departure warning system given	Good architecture for sensor fusion. Testing limited to false alarm rate of departure warning.
DARVIN (2002) [5]	A B	DGPS based maps of roads	Image gradient	match to DGPS data	nonlinear filtering	selected frames from experimentation	Directed towards urban driving. Heavy reliance on GPS data.
Lee et al. (2003) [37], [38]	B	Straight road on flat plane	Edge distribution function	Hough transform to extract lanes	Not discussed	Detection rate of lane departure warning	Robust to lighting. Will not work for circular reflectors.
Apostoloff et al. (2003) [29]	C	Not discussed	lane markers, road edge, color, width	Cue scheduling to determine which cues are used	Particle Filtering via Distillation	Success rate, mean absolute error for position, yaw, and road width.	Possibly fail in conditions of strong cues that contradict each other (i.e. fig. 2b)
Kang et al. (2003) [28]	D	Straight road on flat plane	Edge direction and magnitude	Connected-component analysis, Dynamic programming	Single frame operation	Qualitative comparison to hough transform based techniques, Single images shown	Focuses on showing visual comparison to hough transform based technique.
Nedevschi et al. (2004) [22]	D	3D model based on clothoids and roll angle	edge detection	outlier removal based on 3D location found with stereo camera system, roll angle detected	Kalman filtering	single images from road scenes with clearly marked lane boundaries	Simple edge detection not robust to shadows, occlusions
This paper (2004)	C B	Parabolic approximation on flat plane	Steerable filters, adaptive road template	Statistical and motion based outlier removal	Kalman Filtering	Extensive error evaluation described in section V-B	

This paper



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Steerable Filters

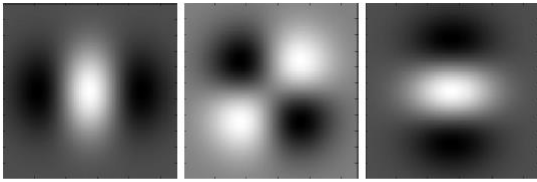


Fig. 7. A basis set for steerable filters based on the second derivatives of a two-dimensional Gaussian.



(a) A highway scene with complex shadowing from trees.



(b) Detection results for lines tuned to the lane angle.

Fig. 9. Filter results when lane markings are shadowed with complex shadows and non-uniform road materials.



(a) A typical highway scene encountered during evaluation.



(b) Results of filtering for circular reflectors.



(c) Results from filter for a line tuned to the lane angle.

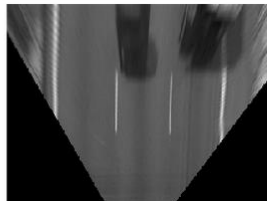
Fig. 8. Application of Steerable filter road marking recognition for circular reflectors and solid lines on a highway

Inverse Perspective Warping (IPM) and Template Matching

IPM: A perspective transformation, to obtain an overview of the road ahead of the vehicle.

=> Easier to do lane boundaries extraction or matching.

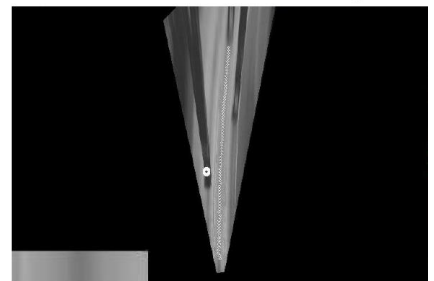
- Curvature detection done by using an intensity template of past images in order to detect the curvature of the road ahead.



Inverse Perspective Warping



(a) Detected lanes with curvature overlaid onto image



(b) Inverse perspective warping showing curvature detection (small white dots) and template (lower left corner)

Fig. 10. Curvature detection in the ViOLET lane tracking [Document1 - Word]

A. System Test-bed Configuration and Test Conditions



Fig. 11. The LISA-Q intelligent vehicle test bed. Inset are close up views of the front camera (left inset) used for detection and tracking and side camera (right inset) used for generating ground truth.

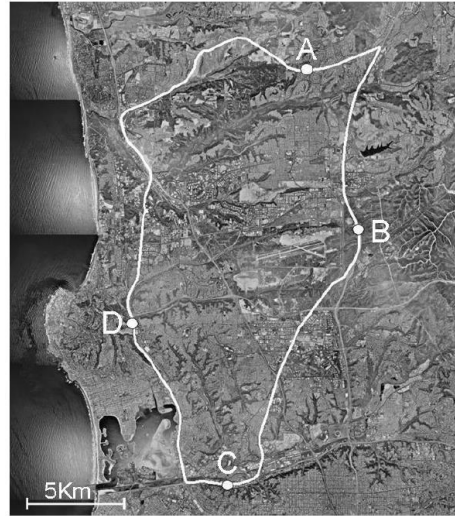


Fig. 14. The 65Km route in San Diego used in the evaluation. The route is overlaid on aerial photography. Points A, B, C, and D are sections of road used in the evaluation (photography courtesy USGS)

Results



Fig. 15. Scenes from dawn (row 1), daytime (row 2), dusk (row 3), and nighttime (row 4) data runs for each of the four sections of road (A, B, C, and D in figure 14). These scenes show the environmental variability caused by road markings and surfaces, weather, and lighting.

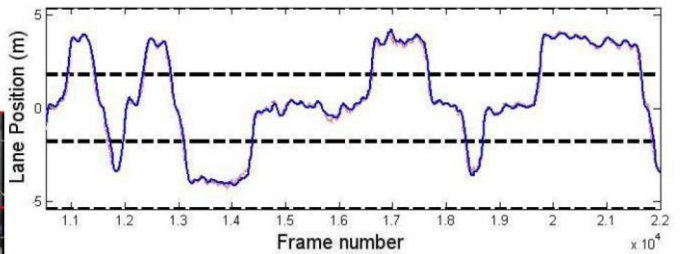


Fig. 12. Detected lateral position in meters (solid blue) superimposed on ground truth (dashed pink) plotted vs. frame number with dashed lines marking the position of lane boundaries for an 11,000 frame (slightly over 6 minute) sequence.

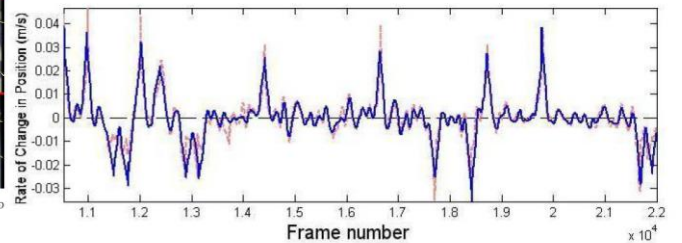


Fig. 13. Detected departure rate in m/s^2 (solid blue) superimposed on ground truth (dashed pink) plotted vs. frame number with dashed line marking the abscissa for the same sequence shown in figure 12.

Detected lanes = Solid blue
Ground truth = Pink dashed line

Challenges: Occlusions and Highlights



Fig. 16. Error due to occlusion of the road by a vehicle on the dusk dataset on road segment C. The red horizontal line shows the proximity of the occluding vehicle detected by the in-vehicle LASER RADAR sensors.



Fig. 17. Scenes from the special case scenarios of complex shadowing (top row) and tunnels (bottom row). These scenes highlight the extreme variability that can occur within short sections of road.

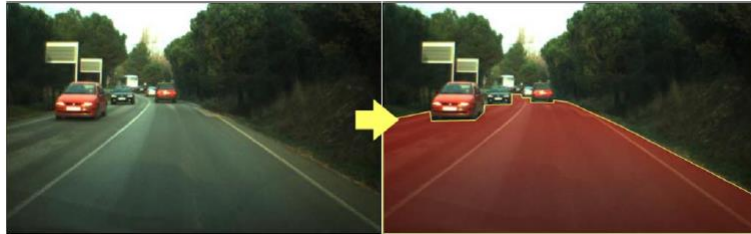
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Road Detection

1. H. Kong, et al. General road detection from a single image, IEEE Transactions on Image Processing, Vol. 19, Issue 8, Aug. 2010. (552 citations)
2. J.M. Alvarez, et al., Road Detection Based on Illuminant Invariance, IEEE Transactions on Intelligent Transportation Systems, 2010. (393 citations)
3. E. Wang et al. Road detection based on illuminant invariance and quadratic estimation. Optik. Elsevier, 2019. (15 citations)

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Road Detection Based on Illuminant Invariance



Goal: Identify all pixels that belong to the road.

Challenges:

- Images from a mobile platform, outdoor: shadows, sunlight, etc.
- Changing background: trees, buildings and many (moving) objects: cars, bikes, pedestrians, dogs, signs, etc.
- Road types in different shapes and forms.

Sensors:

- Monocular => Features: Color, Texture, etc.

J.M. Alvarez, et al. 2010

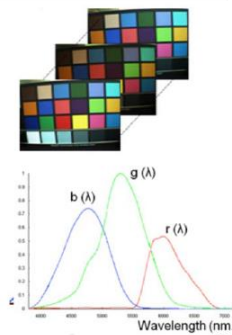
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Road Detection Based on Illuminant Invariance

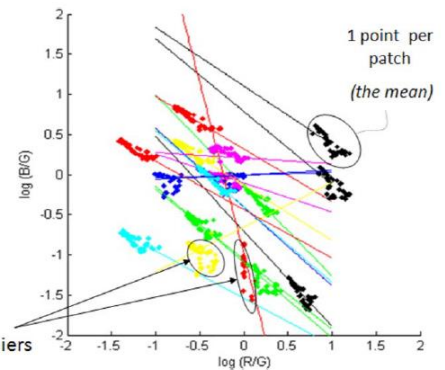


Challenges: Shadows, sunlight, cloudy, etc.

Camera calibration using Macbeth color checker, can not be used for onboard self calibration and image content.



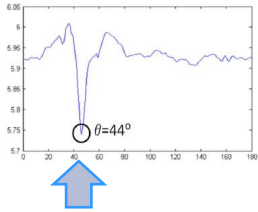
Projection in $\log(R/G)$
 $\log(B/G)$ space along
angle theta (Θ)



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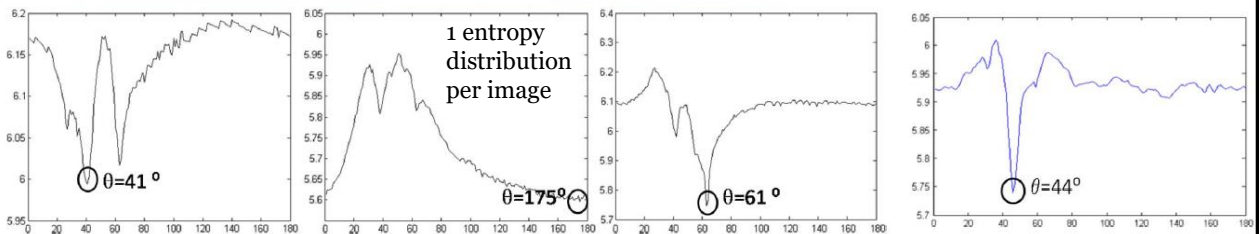
Road Detection Based on Illuminant Invariance

Idea: Projection in $\log(R/G) \log(B/G)$ space along angle theta (Θ)
 => Gives axis where each level corresponds to a chromaticity independent of illumination

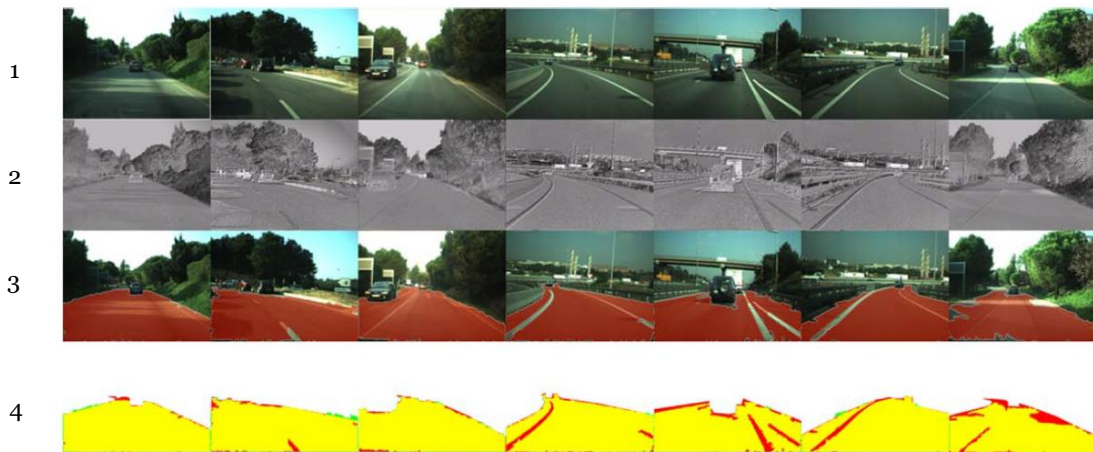


Entropy based camera calibration resulted in Θ is the invariant angle that allows us to compute I a grayscale image invariant to lighting variations.

Road Detection Based on Illuminant Invariance



Entropy based camera calibration: can be used for onboard self calibration and image content.
 Θ is the absolute minimum of the average distribution of entropy values for $\text{Image}_{\text{RGB}}$ (minimization procedure)



1. Original image
2. Illumination Invariant Image
3. Detected Road
4. Handsegmented (yellow) Correctly Classified (green) Falsly Classified (red)

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Fig. 12. Road-detection results. Example results include the following: (First column) Images from a sunny day with annoying shadows and traffic; (second column) images from a wet road without puddles with dim shadows and traffic; (third column) different scenarios; (fourth column) different road shapes; (last column) presence of other vehicles.

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Fig. 13. Examples where our road-detection method currently fails.

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General road detection from a single image

H. Kong et al. 2010



Road in different shapes and forms under different lighting with changes in colors, and textures.

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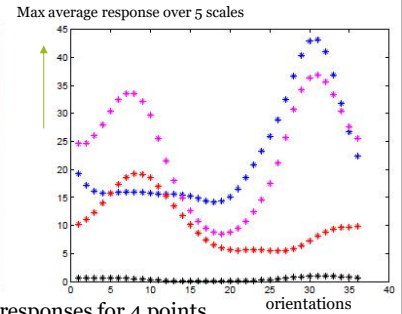
General road detection from a single image

H. Kong et al. 2010

Road in different shapes and forms under different lighting with changes in colors, and textures.

Detection

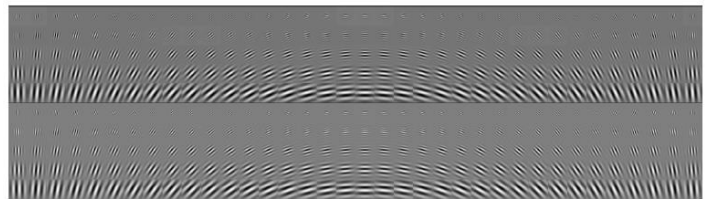
1. Vanishing point estimation of main road
2. Segmentation based on this vanishing point



Gabor complex responses for 4 points.

Voting scheme:

- High-confidence voters using texture orientations resulting from Gabor filters (5 scales 36 orientations)
- Vanishing-point-constrained edge detection for road boundaries



Gabor kernels: real part (row 1-5), imaginary part (row 6-10)

General road detection from a single image

H. Kong et al. 2010

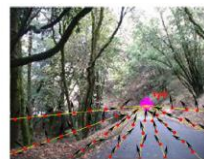
Road in different shapes and forms under different lighting with changes in colors, and textures.

Detection

1. Vanishing point estimation of main road
2. Segmentation based on this vanishing point



Line segments



vanishing point with rays



orientation consistent rays



compute color difference of neighboring regions

Voting scheme:

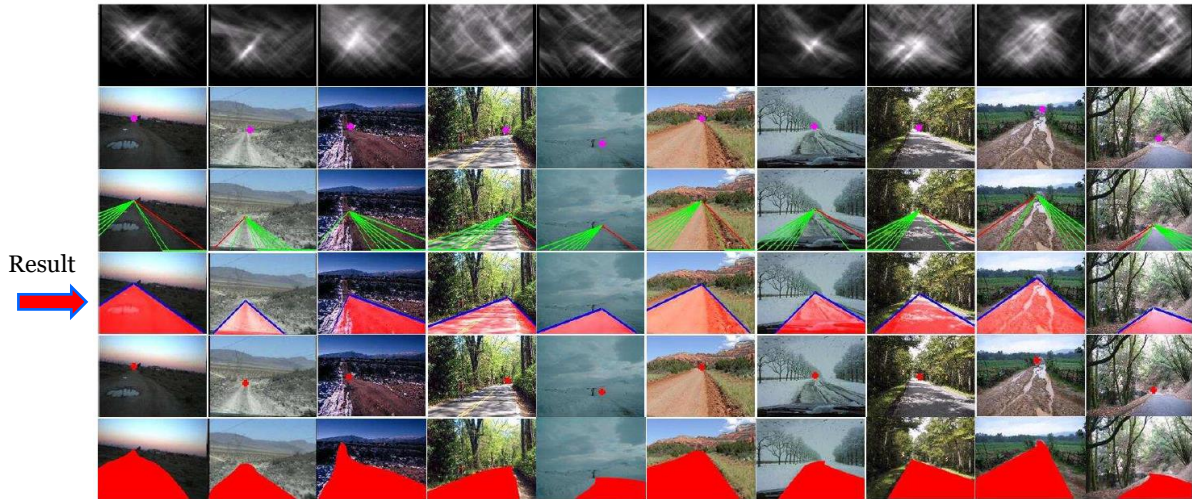
- High-confidence voters using texture orientations resulting from Gabor filters (5 scales 36 orientations)
- Vanishing-point-constrained edge detection for road boundaries



dominant border (red)
=> vanishing point adaptation

General road detection from a single image

H. Kong et al. 2010

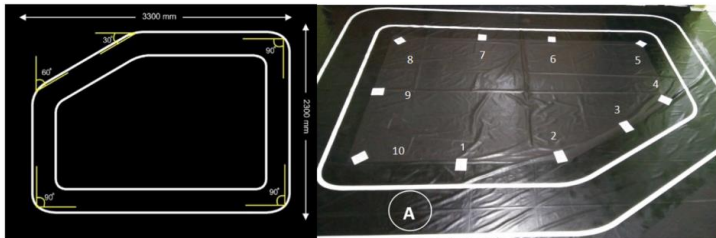
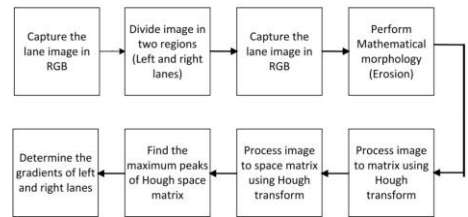
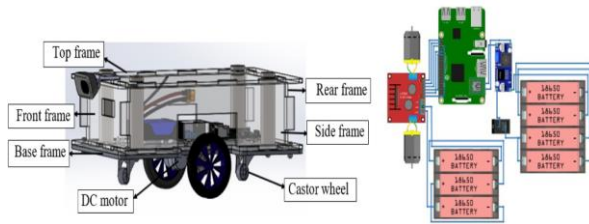


Last row: ground truth..

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Lane Tracking

- M. Munadi et al. Automated guided vehicle (AGV) lane-keeping assist based on computer vision, and fuzzy logic control under varying light intensity. Results in Engineering, Elsevier, 2024.



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Image Processing using OpenCV



Core module: the basic building blocks of this library for manipulating the images on a pixel level.

Imgproc module: the image processing (manipulation) functions inside OpenCV.

High Level GUI and Media (highgui module)

Image Input and Output (imgcodecs module)

Video Input and Output (videoio module)

Camera calibration and 3D reconstruction (calib3d module)

2D Features framework (feature2d module): feature points detectors, descriptors and matching framework found inside OpenCV.

Video analysis (video module) algorithms usable on your video streams like motion extraction, feature tracking and foreground extractions.

Object Detection (objdetect module) face detectors, etc.

Deep Neural Networks (dnn module)

Machine Learning (ml module) machine learning classes for statistical classification, regression and clustering of data.

Graph API (gapi module)

Computational photography (photo module) for advanced photo processing.

Images stitching (stitching module) create photo panoramas and more with OpenCV stitching pipeline.

GPU-Accelerated Computer Vision (cuda module); OpenCV iOS:

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Lane Tracking

Some example project for detecting road features using OpenCV:

<https://navoshta.com/detecting-road-features/> by Alex Staravoitau (2017)



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Overview Processing Pipeline

Camera calibration

- Each camera gives image distortions, these can be rectified using information from a camera calibration. OpenCV has functionality to calibrate and correct camera images. Calibration is done using chessboard images.

Edge detection

- OpenCV has many different edge detectors using gradient and color information. These edges can be used for the detection of structures such as lines etc.

Perspective transformation

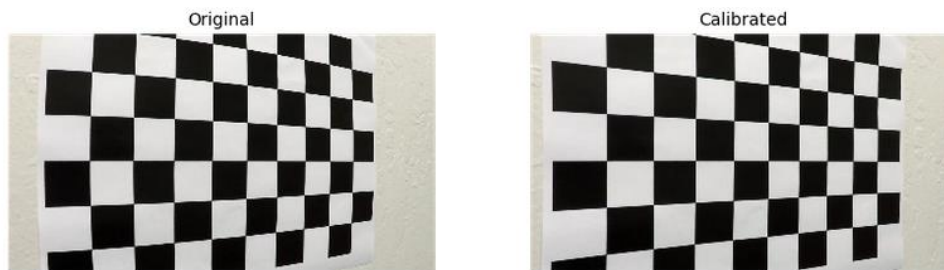
- A perspective transformation, can be used to obtain an overview of the road ahead of the vehicle. This can make the problem of lane boundaries extraction easier.

Fitting boundary lines

- The resulting frame pixels are determined that may belong to lane boundaries.
- These are then used to approximate lines, road properties and vehicle position.
- Furthermore, a rough estimate on road curvature and vehicle position within the lane is determined using known road dimensions.

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Processing Pipeline: Camera Calibration

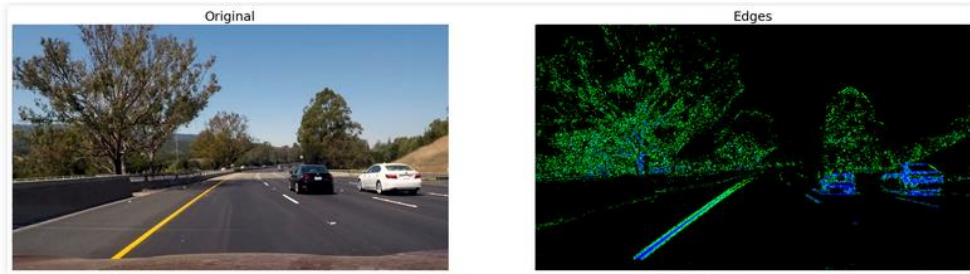


Original vs. calibrated images

```
... cv2.findChessboardCorners(image, (9, 6), None) // Inner corners 9x6
... cv2.calibrateCamera( pattern_points, image_points, (image.shape[1], image.shape[0]), None, None)
corrected_image = cv2.undistort(image, self.camera_matrix, self.dist_coefficients, None, self.camera_matrix)
```

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Processing Pipeline: Edge Detection



Original vs. highlighted edges

Gradient Absolute Values, Ranges within certain magnitudes, Gradient Directions

- Sobel Operator (using a convolutional Kernel)

Color Ranges

- HSL Color Space: Hue, Saturation, and Lightness (for road detection, etc.)

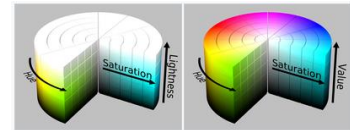


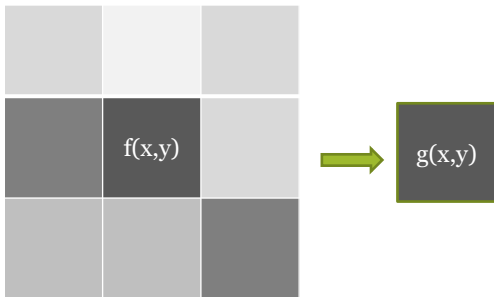
Fig. 2a. HSL cylinder.

Fig. 2b. HSV cylinder.

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Image Processing using Convolutional Kernel

$$g(x, y) = \omega * f(x, y) = \sum_{dx=-a}^a \sum_{dy=-b}^b \omega(dx, dy) f(x + dx, y + dy)$$



Operation	Kernel ω	Image result $g(x,y)$
Identity	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	
Edge detection	$\begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}$	
	$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix}$	
	$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$	
Sharpen	$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$	

[https://en.wikipedia.org/wiki/Kernel_\(image_processing\)](https://en.wikipedia.org/wiki/Kernel_(image_processing))

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Processing Pipeline: Perspective Transformation



Original vs. bird's eye view

```
.... transform_matrix = cv2.getPerspectiveTransform(source, destination)
.... image = cv2.warpPerspective(image, transform_matrix, (w, h))
```

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Processing Pipeline: Perspective Transformation



Boundary detection pipeline

Left: The *original* image after the camera calibration and perspective transform.

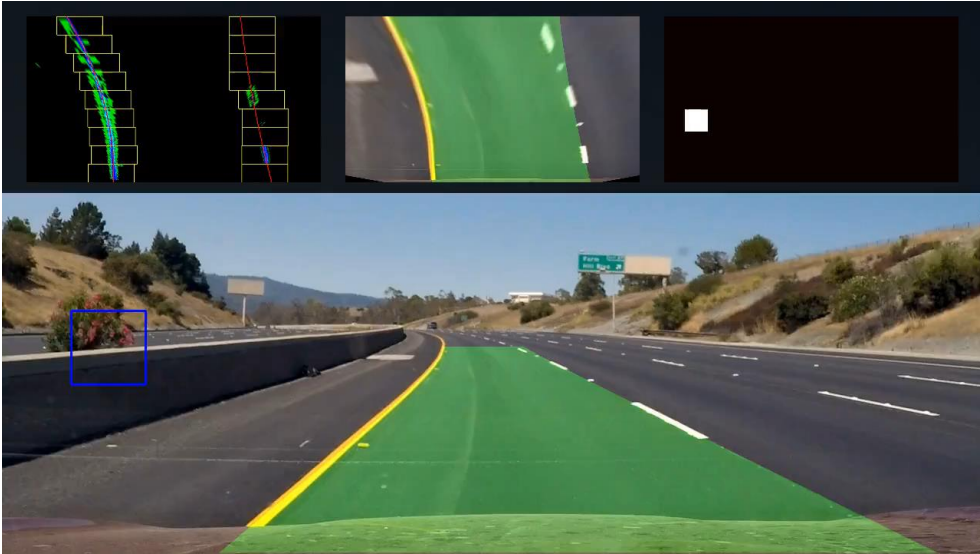
Right: After edge detection with edges highlighted in **green** and **blue**.

Scanning windows boundaries for areas with pixel that may belong to lines are highlighted in **yellow**,

A second order polynomial approximation of the collected points in **red**.

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Lane and Vehicle Tracking



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Some remarks

Alex Staravoitau:

“This clearly is a very naive way of detecting and tracking road features, and wouldn’t be used in real world application as-is, since it is likely to fail in too many scenarios: “

- Going up or down the hill.
- Changing weather conditions.
- Worn out lane markings.
- Obstruction by other vehicles or vehicles obstructing each other.
- Vehicles and vehicle positions different from those classifier was trained on.
- ...

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Organization and Overview

Lecturer:

Dr Erwin M. Bakker (erwin@liacs.nl)
Room LIACS Media Lab (LML)
Please email for a meeting.

Period: February 11th - May 13th 2025

Time: Tuesday 11.15 - 13.00

Place (Rooms): Van Steenis F1.04

Exceptions:

Gorlaeus Building BM.1.33 on April 1st

Gorlaeus Building BM.1.23 on May 20th

Teaching assistants:

TBA

Schedule (tentative, visit regularly):

Date	Subject
11-2	Introduction and Overview
18-2	Locomotion and Inverse Kinematics
25-2	Robotics Sensors and Image Processing
4-3	SLAM + Workshop@Home
11-3	Robotics Vision + Introduction Mobile Robot Challenge
18-3	Project Proposals I (by students)
25-3	Project Proposals II (by students)
1-4	Robotics Reinforcement Learning + RL Workshop@Home
8-4	Project Progress Reports I
15-4	Project Progress Reports II
22-4	Mobile Robot Challenge I
29-4	Mobile Robot Challenge II
6-5	TBA
13-5	Project Demos I
20-5	Project Demos II
27-5	Project Deliverables



Grading (6 ECTS):

- Presentations and Robotics Project (60% of grade).
- Class discussions, attendance, 2 assignments (pass/no pass)
- 2 Workshops (0-10) (20% of the grade).
- Mobile Robot Challenge (0-10) (20% of the grade)
- ***It is necessary to be at every class and to complete every workshop and assignment.***

Website: <http://liacs.leidenuniv.nl/~bakkerem2/robotics/>

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Robotics Project Proposals Presentations

Tuesday 18-3 and 25-3 2025

Present your Robotics Project Proposal during a **5 minute (max)** talk. Clearly state the title of your project, the team members, your goals, how you will pursue them, what are the challenges and what at least can and should be delivered on the demo day on **May 13th and May 27th 2025**.

Note: Groups of 1-5 members are allowed.

Please form your project group in the coming week.

The presentation should contain slides for:

1. Title and group members.
2. Goal of the project: **what is novel? Refer to at least one relevant and published research paper!**
3. How will you pursue these goals: division of work per group member
4. What are the challenges of your project.
5. What at least can and should be delivered on the demo days on **May 13th and May 27th 2025**.

The LIACS Media Lab can support your project with some materials for your project. Please clearly state any materials that you would need for your proposal. **Note that these materials are limited so project goals may need to be adjusted accordingly.**

Each presentation will be followed by a short class discussion.

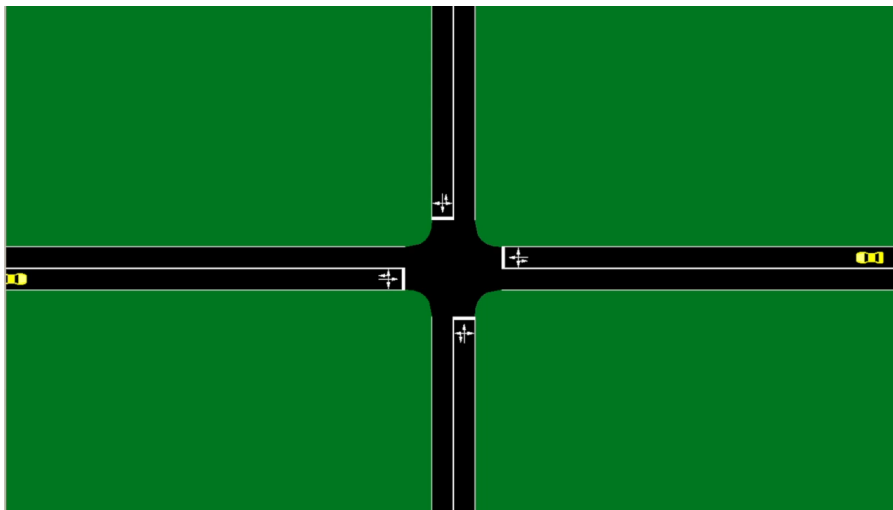
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Previous Projects

- | | | |
|--|--|---|
| <ol style="list-style-type: none"> 1. Evolutionary Locomotion 2. Nao plays Tic-Tac-Toe 3. Slam Robot Project. 4. Dolphin Drone: Drone Recognition and Maneuvering with Hoops. 5. Delivery Drone. 6. Programming a NAO to play a tune using a xylophone. 7. Floor mapping with Swarm Robotics 8. Tootballing Yetiborg 9. Cat Flap Opening Based on Audio/Video/RFID 10. DrawBot 11. Traffic coordination (simulation). 12. Plane filling curves (simulation). | <ol style="list-style-type: none"> 1. AimBot 2. Artificial Muscles 3. Ball Tracking Car 4. BorrelBot 5. Fetch Bot 6. Floor Mapping Robot 7. Gesture Control Pachenko 8. Hexapod 9. Nao Pose 10. Position Estimation 11. Race Car Training 12. Face Touch | <ol style="list-style-type: none"> 1. Autonomous driving copilot 2. Self Balancing robot 3. Tennis playing robot 4. PongBot 5. Bipedal Balancing Robot 6. Chess Game 7. Etc. |
|--|--|---|

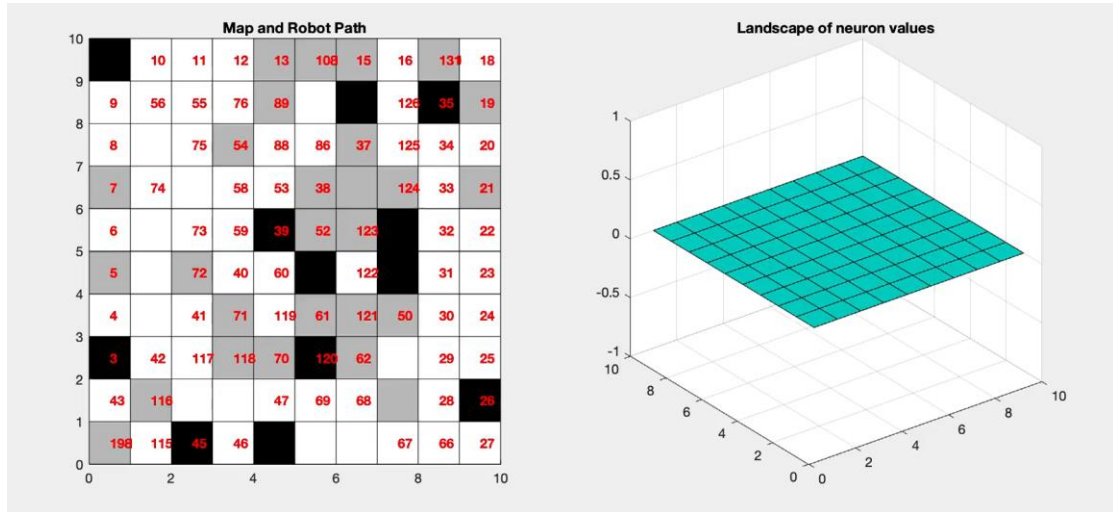
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Traffic coordination (simulation).



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Roombas with Brains: Neural Networks for Coverage Path Planning



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Gesture Controlled Pachenko

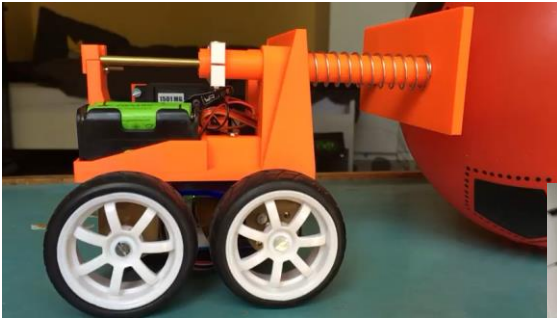
Gesture Controlled Pachinko Game

Aaron Dunlea, Nathan van der Putten, Malte Wilhelm



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Traffic coordination (simulation).

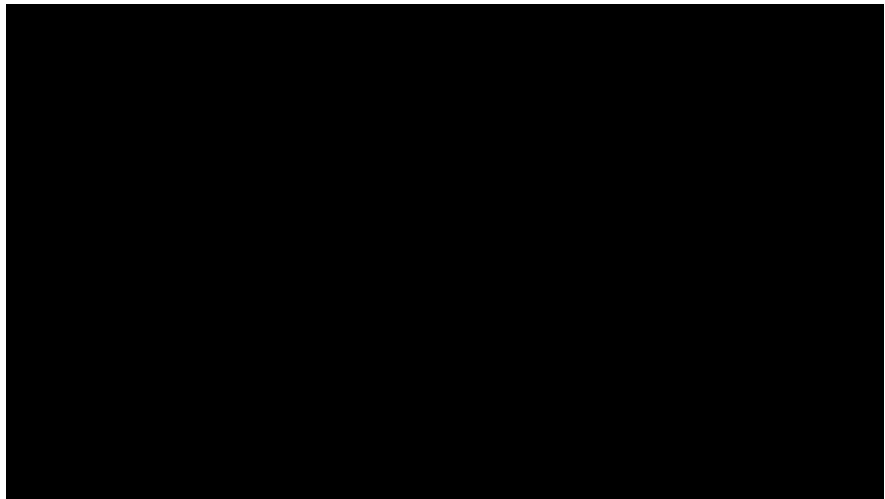


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DrawBot
AimBot
FetchBot

Cellular Automaton: [https://youtu.be/maC1eo8 -II](https://youtu.be/maC1eo8-II)
Dragon Curve: https://youtu.be/9ilDP_pvDEk

<https://vimeo.com/425043774>



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S.P.I.N. - Spider Python INator

Marcel Huijben (s1780107)
Martijn Swenne (s1923889)
Sebastiaan Alvarez Rodriguez (s1810979)
Robin Voetter (s1835130)

Autonomous driving copilot


Gesture control and autonomous driving system

Siwen Tu, Chenyu Shi, Shupe Li, Lin He , Ruilin Ma



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Tennis Simulation



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PongBot

Chess Game Recognition

Ivar Martens
s2990806

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Chess Playing

Bipedal Balancing Robot

Leiden Dynamics

Max Boone (s2081318)
Guus Kleinlein (s3745880)
Sven Hepkema (s2454556)

Final Project - Robotics 2024

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Bipedal Balancing Robot

References

1. Joel C. McCall and Mohan M. Trivedi, Video Based Lane Estimation and Tracking for Driver Assistance: Survey, System, and Evaluation. IEEE Transactions on Intelligent Transportation Systems, 2006
2. A. Bar Hillel, R. Lerner, D. Levi, G. Raz, Recent progress in road and lane detection: a survey. Machine Vision and Applications (2014) 25:727–745
3. J. Fritsch, T. Kühnl, F. Kummert, Monocular Road Terrain Detection by Combining Visual and Spatial Information. IEEE Transactions on Intelligent Transportation Systems, 2014.
4. J. Sattar, J. Mo, SafeDrive: A Robust Lane Tracking System for Autonomous and Assisted Driving Under Limited Visibility. January 31, 2017 (<https://arxiv.org/abs/1701.08449>)
5. <https://navoshta.com/detecting-road-features/> by Alex Staravoitau
6. OpenCV.org