PLANNING AND CONTROL OF AUTONOMOUS VEHICLES

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INTRODUCTION

Automation Levels

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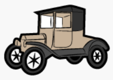
Introduction

LEVEL 0  There are no autonomous features.	**LEVEL 1**  These cars can handle one task at a time, like automatic braking.	**LEVEL 2**  These cars would have at least two automated functions.
LEVEL 3  These cars handle "dynamic driving tasks" but might still need intervention.	**LEVEL 4**  These cars are officially driverless in certain environments.	**LEVEL 5**  These cars can operate entirely on their own without any driver presence.

Autonomous Vehicle

Future Evolution

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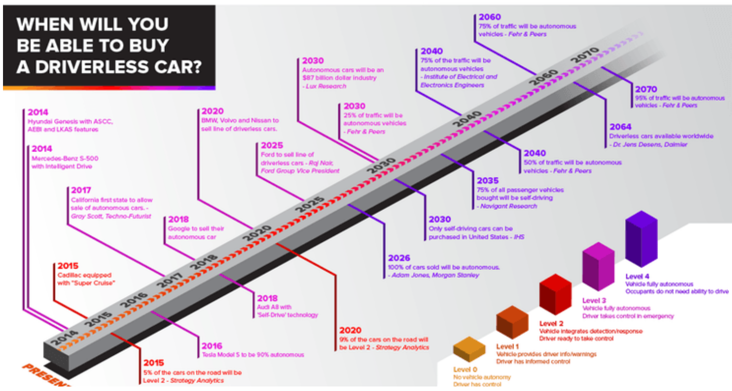
Introduction



Autonomous Vehicle

Smart Vehicles

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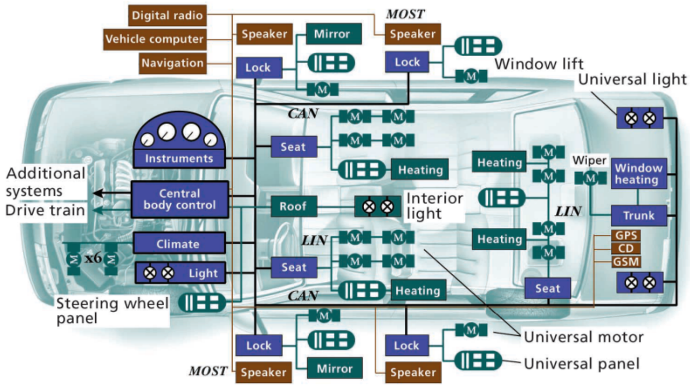
Introduction



CAN Controller area network
GPS Global Positioning System
GSM Global System for Mobile Communications
LIN Local interconnect network
MOST Media-oriented systems transport

Main Modules in Autonomous Vehicle

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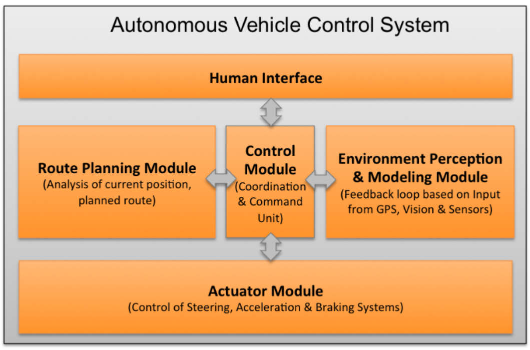
Introduction



Control of Autonomous Vehicle

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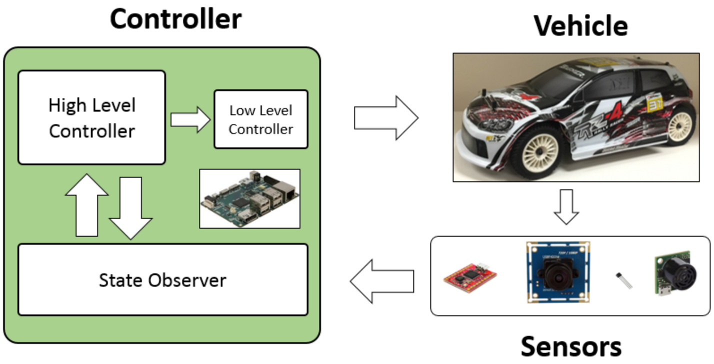
Introduction



Control of Autonomous Vehicle

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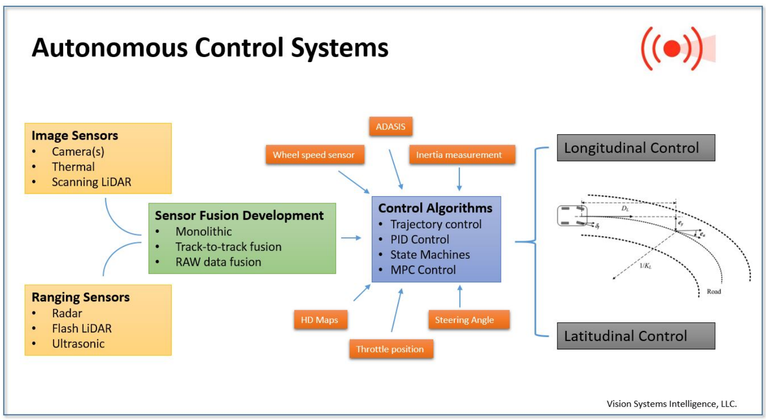
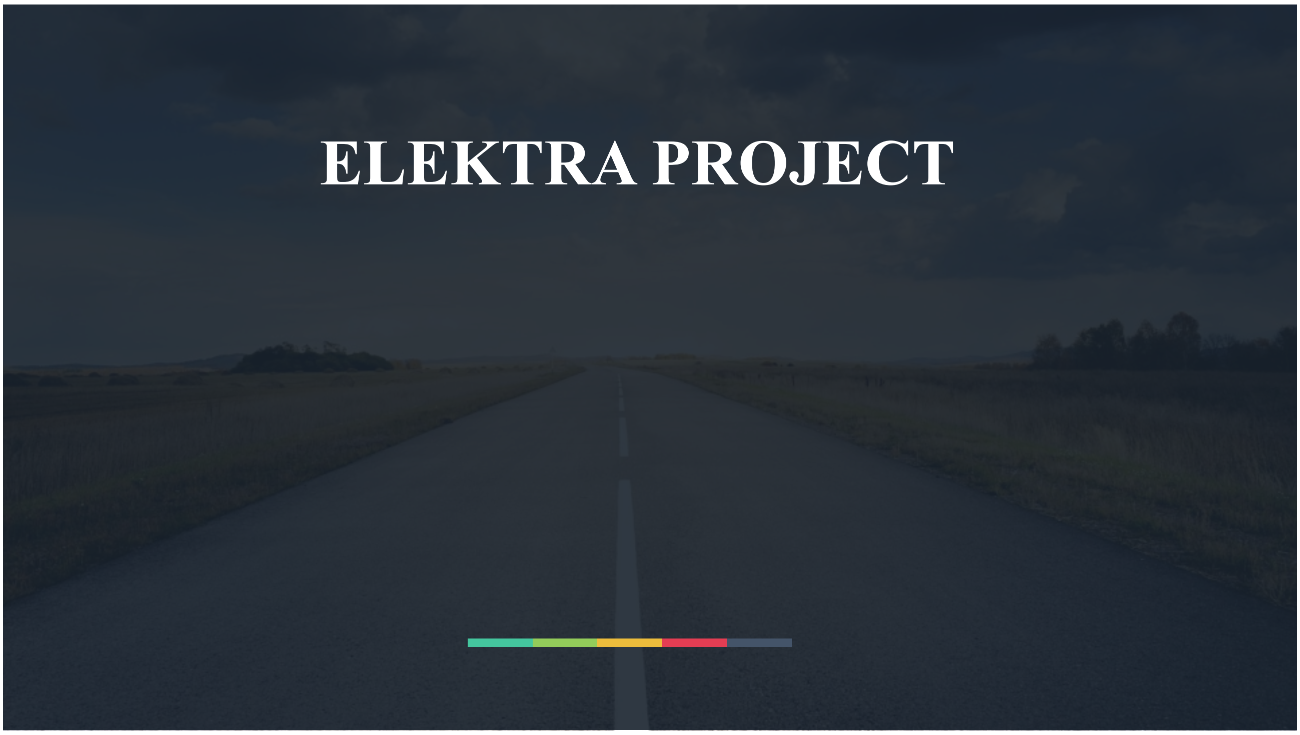
Introduction





Elektra Autonomous Vehicle

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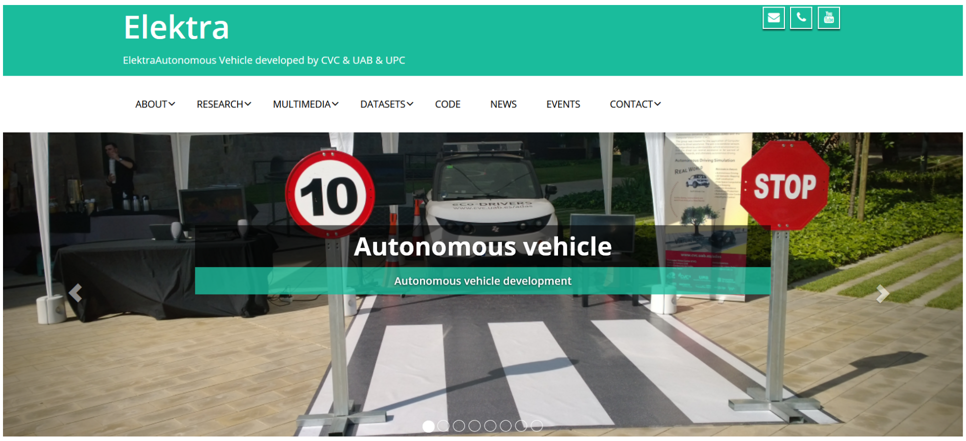
CVC, UAB and UPC project



Autonomous Vehicle

Elektra Autnomous Vehicle

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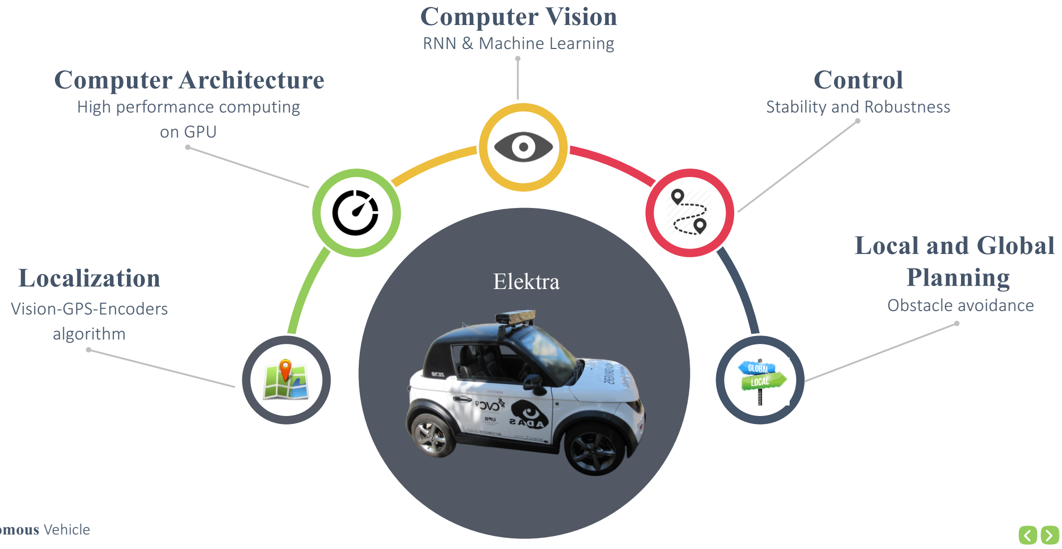
Development groups



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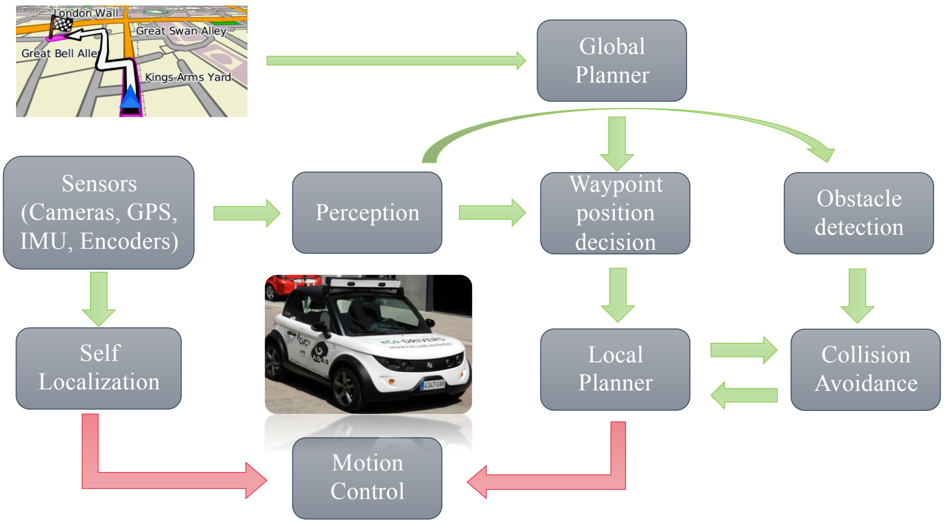
System architecture



Autonomous Vehicle

Development Tools

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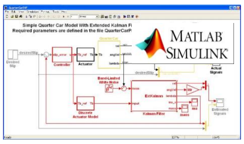
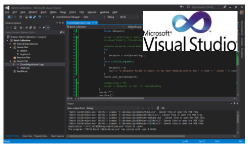
Flow



Matlab / Simulink
Known and powerful tool

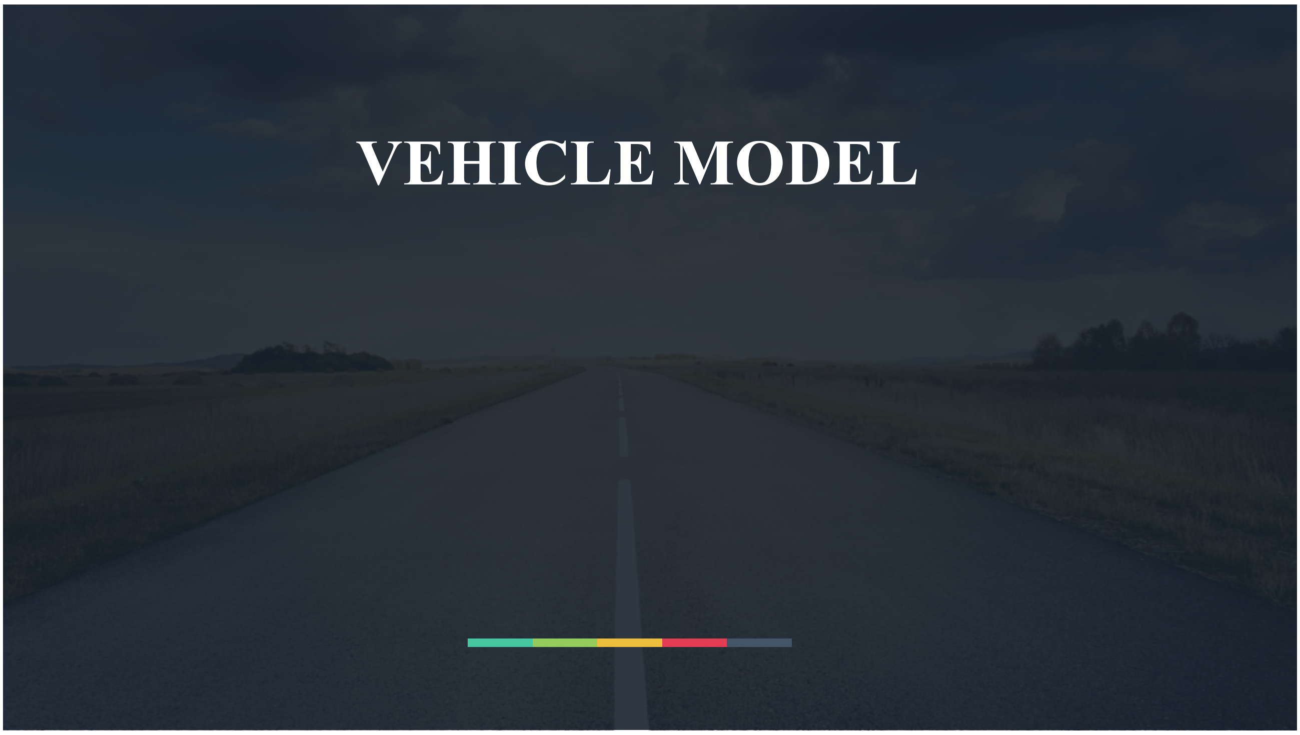
Unity 5.1.3
3D simulator
C#



Microsoft Visual Studio
Programming environment
C++

ROS
Real vehicle tool
C++

Autonomous Vehicle



Kinematic and Dynamic Model

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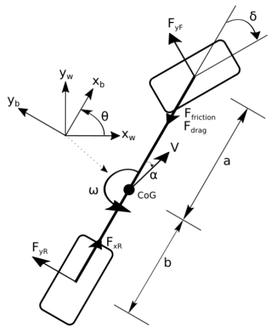
Vehicle Model



Kinematic model

$$\begin{cases} \dot{x}_w = v \cdot cos(\theta) \\ \dot{y}_w = v \cdot sin(\theta) \\ \dot{\theta}_w = \frac{v}{\mathrm{a}} \cdot tan(\delta) \end{cases}$$

Dynamic model

$$\begin{cases} \dot{v} = \frac{F_{xR}\cos(\alpha)+F_{yF}\sin(\alpha-\delta)+F_{yR}\sin(\alpha)-F_{drag}-F_{friction}}{\mathrm{m}} \\ \dot{\alpha} = \frac{-F_{xR}\sin(\alpha)+F_{yF}\cos(\alpha-\delta)+F_{yR}\cos(\alpha)}{\mathrm{m}v} - \omega \\ \dot{\omega} = \frac{F_{yF}\mathrm{a}\cos(\delta)+F_{yR}\mathrm{b}}{\mathrm{I}} \end{cases}$$

Autonomous Vehicle

LPV models

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- \- Linear Parameter Varying (LPV) systems are linear systems whose state-space matrices are functions of some parameter vector *θ(τ)*:

$$\sigma.x(\tau) = A(\theta(\tau))x(\tau) + B(\theta(\tau))u(\tau)$$
$$y(\tau) = C(\theta(\tau))x(\tau) + D(\theta(\tau))u(\tau)$$

- \- The LPV system is said to be *polytopic* if:

$$\begin{pmatrix} A(\theta(\tau)) & B(\theta(\tau)) \\ C(\theta(\tau)) & D(\theta(\tau)) \end{pmatrix} = \sum_{j=1}^{N} \alpha_j(\theta(\tau)) \begin{pmatrix} A_j & B_j \\ C_j & D_j \end{pmatrix}, \quad \begin{matrix} \sum_{j=1}^{N} \alpha_j(\theta(\tau)) = 1 \\ \alpha_j(\theta(\tau)) \geq 0 \quad \forall j \end{matrix}$$

Autonomous Vehicle

LPV Kinematic and Dynamic Model

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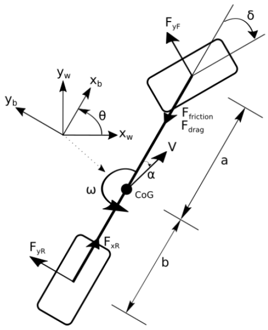
Vehicle Model



Kinematic model

$$\dot{\boldsymbol{x}}_C = \boldsymbol{A}_C(\omega, v_d, \theta_e)\boldsymbol{x}_C + \boldsymbol{B}_C\boldsymbol{u}_C - \boldsymbol{B}_C\boldsymbol{r}_C$$

where

$$\boldsymbol{A}_C\left(\omega, v_d, \theta_e\right) = \begin{bmatrix} 0 & \omega & 0 \\ -\omega & 0 & v_d\frac{\sin\theta_e}{\theta_e} \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{B}_C = \begin{bmatrix} -1 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix}.$$

Dynamic model

$$\dot{\boldsymbol{x}} = \boldsymbol{A}(\delta, v, \alpha)\boldsymbol{x} + \boldsymbol{B}(\delta, v, \alpha)\boldsymbol{u}_D + \boldsymbol{E}F_{fr}$$

where:

$$\boldsymbol{A}(\delta, v, \alpha) = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ 0 & A_{22} & A_{23} \\ 0 & A_{32} & A_{33} \end{bmatrix}$$

Autonomous Vehicle

Problems to be solved

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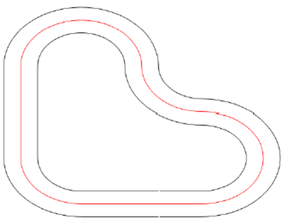
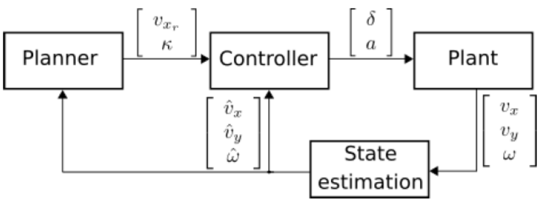
Testing circuit



Motion planning & control diagram



Autonomous Vehicle

Trajectory Planning using MPC

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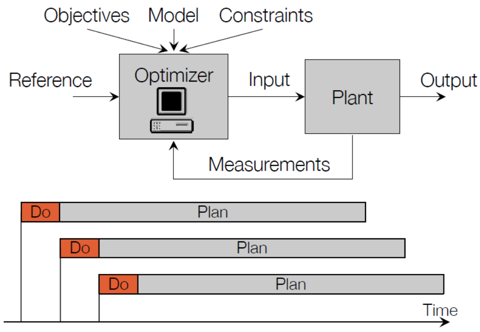
Planning

$$\underset{\Delta U_k}{\text{minimize}} \quad J_k = \sum_{i=0}^{N-1} \left(x_{k+i}^T Q x_{k+i} + \Delta u_{k+i} R \Delta u_{k+i} \right) + x_{k+N}^T P x_{k+N}$$

subject to

$$x_{k+i+1} = f(x_{k+i}, u_{k+i})$$
$$u_{k+i} = u_{k+i-1} + \Delta u_{k+i} \qquad i = 0, \ldots, N-1$$
$$N = L_{track}/ds$$
$$\Delta U_k \in \Delta\Pi$$
$$U_k \in \Pi$$
$$x_{k+N} \in \chi$$
$$\dot{x}_{k+N} \in \Xi$$



Trajectory Planner for Racing

Algorithm

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NLMPC

$$\underset{X,U}{\text{minimize}} \quad \mathrm{J_k} = -\sum_{i=0}^{N} \frac{v_x \cos\theta_e - v_y \sin\theta_e}{1 - y_e \kappa}$$

subject to

$$x_{k+i+1} = f(x_{k+i}, u_{k+i})$$
$$y_e \in [\overline{y_e}, \underline{y_e}]$$
$$u \in [\overline{u}, \underline{u}]$$
$$\left(\frac{\dot{v_x}}{\dot{v}_{x\,max}}\right)^2 + \left(\frac{\dot{v_y}}{\dot{v}_{y\,max}}\right)^2 - 1 \leq 0$$

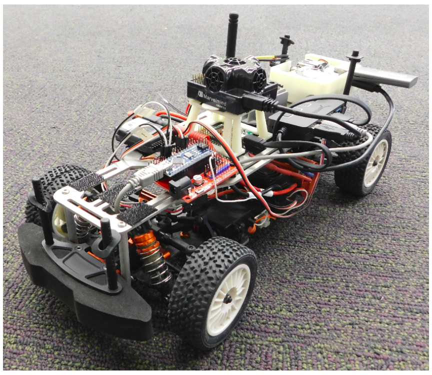
where $x = [v_x, v_y, \omega, y_e, \theta_e]$
and $u = [\delta, a]$

MPC

$$\underset{X,U}{\text{minimize}} \quad \mathrm{J_k} = -\sum_{i=0}^{N} \left(x_{k+i}^T Q x_{k+i} + q^T x_{k+i}\right)$$

subject to

$$x_{k+i+1} = A_i x_{k+i} + B_i u_{k+i}$$
$$y_e \in [\overline{y_e}, \underline{y_e}]$$
$$u \in [\overline{u}, \underline{u}]$$
$$\dot{v_x} \in [\overline{\dot{v_x}}, \underline{\dot{v_x}}]$$
$$\dot{v_y} \in [\overline{\dot{v_y}}, \underline{\dot{v_y}}]$$
$$0 \leq -m\dot{v_y} + n - \dot{v_x}$$
$$0 \leq m\dot{v_y} + n - \dot{v_x}$$



Autonomous Vehicle

Trajectory Planner in Simulation

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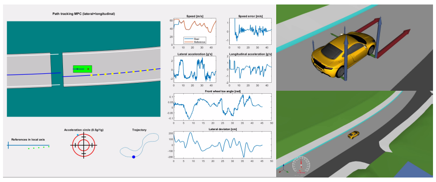

Trajectory Planner in Simulation

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NL-MPC kinematic planner.mp4

Trajectory Planner in a Real Scenario

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COMPLETED_result_Berkeley.mp4

Autonomous Vehicle

Automatic Control Scheme

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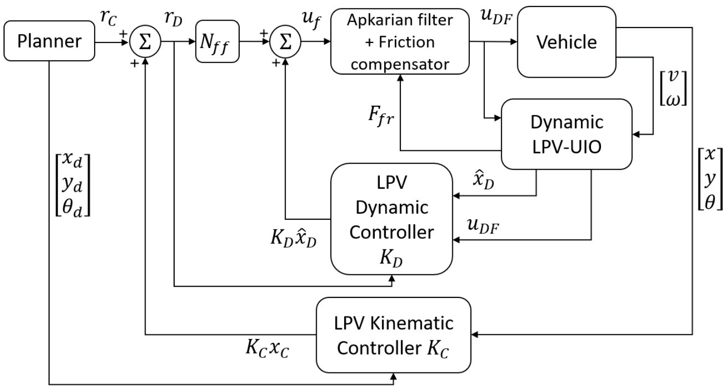
LPV Control



Automatic Control

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LPV Control

Open-loop system

$$\dot{e} = \begin{pmatrix} \omega y_e - v_d cos\theta_e + v \\ -\omega x_e + v_d sin\theta_e \\ \omega_d - \omega \end{pmatrix}$$

Control law

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = -\begin{pmatrix} k_1 & 0 & -v_d \dfrac{\cos\theta_e}{\theta_e} \\ 0 & k_2 v_d \dfrac{\sin\theta_e}{\theta_e} & k_3 \end{pmatrix} \begin{pmatrix} x_e \\ y_e \\ \theta_e \end{pmatrix} + \begin{pmatrix} 0 \\ \omega_d \end{pmatrix}$$

Closed-loop system

$$\dot{e} = \begin{pmatrix} -k_1 & \omega & 0 \\ -\omega & 0 & v_d \dfrac{\sin\theta_e}{\theta_e} \\ 0 & -k_2 v_d \dfrac{\sin\theta_e}{\theta_e} & -k_3 \end{pmatrix} e$$

Automatic Control

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LPV Observer

Proposition 1. *Let the observer tuning parameters* $\boldsymbol{Q} = \boldsymbol{Q}^T \geq 0$, $\boldsymbol{R} = \boldsymbol{R}^T > 0$, *the optimal performance bound* $\gamma > 0$, *the decay rate* $\lambda > 0$, *the output matrix* $\boldsymbol{C}$ *in* (18) *and the matrices* $\boldsymbol{A}_i$ *in* (24). *Then, the polytopic observer gains in* (27) *are obtained by finding* $\boldsymbol{Y}$ *and* $\boldsymbol{W}_i$ *satisfying the following LMIs*

$$\begin{bmatrix} \boldsymbol{Y}\boldsymbol{A}_i + \boldsymbol{A}_i^T\boldsymbol{Y} - \boldsymbol{W}_i\boldsymbol{C} - \boldsymbol{C}^T\boldsymbol{W}_i^T + \boldsymbol{Y}2\lambda & \boldsymbol{Y}(\boldsymbol{Q}^{\frac{1}{2}})^T & \boldsymbol{W}_i \\ \boldsymbol{Q}^{\frac{1}{2}}\boldsymbol{Y} & -\boldsymbol{I} & 0 \\ \boldsymbol{W}_i^T & 0 & -\boldsymbol{R}^{-1} \end{bmatrix} < 0$$

$$\begin{bmatrix} \gamma\boldsymbol{I} & \boldsymbol{I} \\ \boldsymbol{I} & \boldsymbol{Y} \end{bmatrix} > 0\,, \qquad i = 1, ..., 2^{n_{Sv}} \tag{28}$$

considering $\boldsymbol{Y} = \boldsymbol{Y}^T > 0$ *and applying the transformation* $\boldsymbol{L}_i = \boldsymbol{Y}^{-1}\boldsymbol{W}_i$.

$$\boldsymbol{L}(\boldsymbol{\Phi}) = \sum_{i=1}^{2^{n_\Phi}} \mu_i(\boldsymbol{\Phi})\boldsymbol{L}_i$$

Automatic Control

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LPV Control

Proposition 2. *Given the LQR parameters* $\boldsymbol{Q} = \boldsymbol{Q}^T \geq 0$, $\boldsymbol{R} = \boldsymbol{R}^T > 0$, *the optimal performance bound* $\gamma > 0$, *the decay rate* $\eta > 0$ *and the matrices* $\boldsymbol{A}_{D_i}$ *obtained using* (24). *Then, the polytopic control gains in* (29) *are obtained by finding* $\boldsymbol{P}$ *and* $\boldsymbol{W}_i$ *satisfying the following LMIs*

$$\boldsymbol{A}_{D_i}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A}_{D_i} - (\boldsymbol{B}_D\boldsymbol{W}_i)^T - \boldsymbol{B}_D\boldsymbol{W}_i + 2\eta\boldsymbol{P} < 0$$

$$\begin{bmatrix} \boldsymbol{W}_i^T\boldsymbol{R}\boldsymbol{W}_i & \boldsymbol{P}(\boldsymbol{Q}^{\frac{1}{2}})^T \\ \boldsymbol{P} & (-\boldsymbol{Q}^{\frac{1}{2}})^{-1} \end{bmatrix} < 0\,, \qquad i = 1, ..., 2^{n_\Phi}$$

$$0 < \boldsymbol{P} < \gamma \tag{30}$$

and applying the transformation $\boldsymbol{K}_{D_i} = \boldsymbol{W}_i\boldsymbol{P}^{-1}$.

$$\boldsymbol{K}_D(\boldsymbol{\Phi}) = \sum_{i=1}^{2^{n_\Phi}} \mu_i(\boldsymbol{\Phi})\boldsymbol{K}_{D_i}$$

Results

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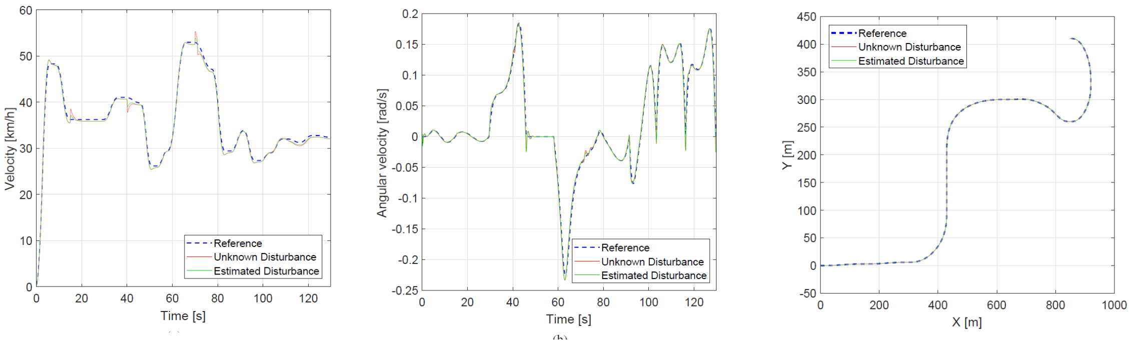

Autonomous Vehicle

Results

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Scenarios

Experimental Results

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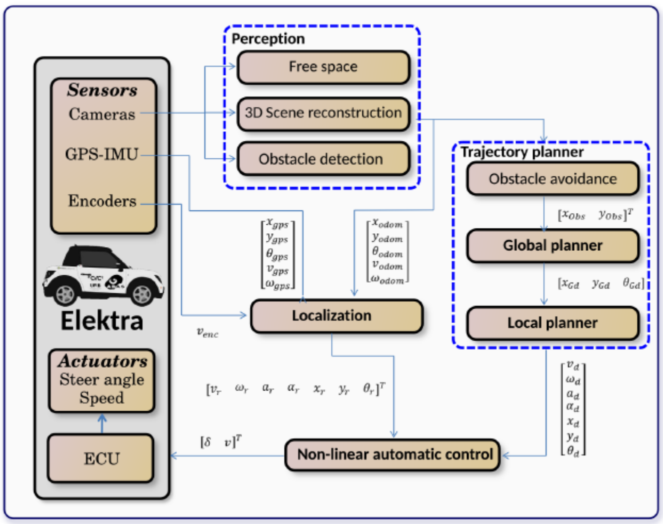
Real vehicle diagram



Experimental Results

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First tests

Elektra autonomous vehicle

Experimental Results

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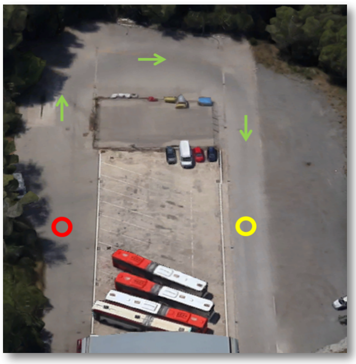
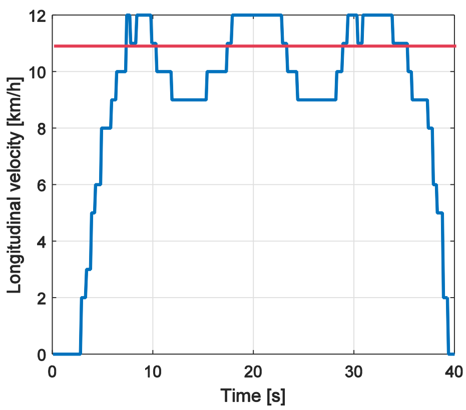
Real test





Elektra autonomous vehicle

Experimental Results

Real test

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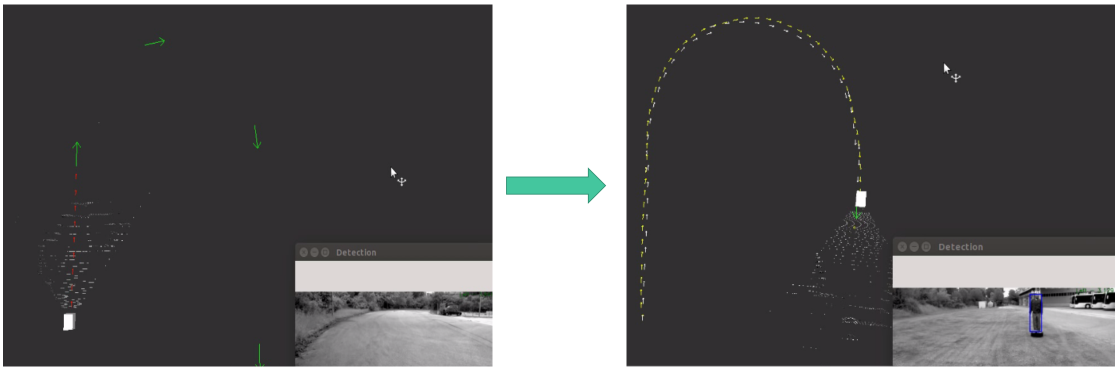

Elektra autonomous vehicle

Experimental Results

Real test

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Integration with Learning

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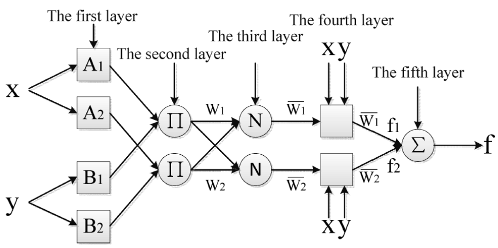

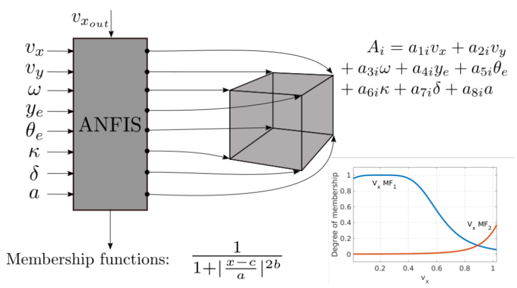

Autonomous Vehicle

Application to a real car

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Applus⊕ IDIADA

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Autonomous Vehicle

Driverless Competition

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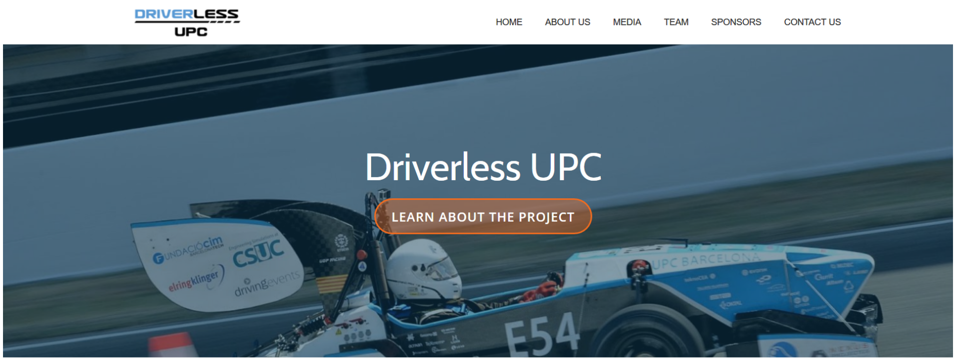

Autonomous Vehicle

SEAT Autonomous Driving Challenge

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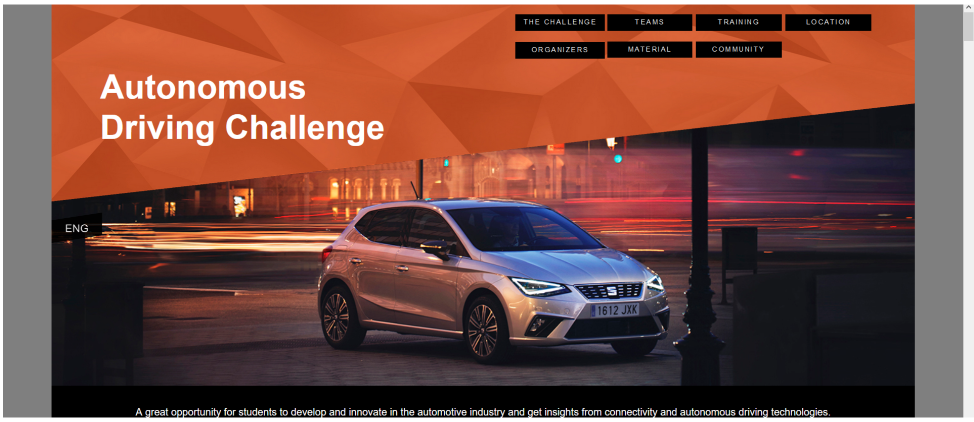

CARLA Autonomous Driving Challenge

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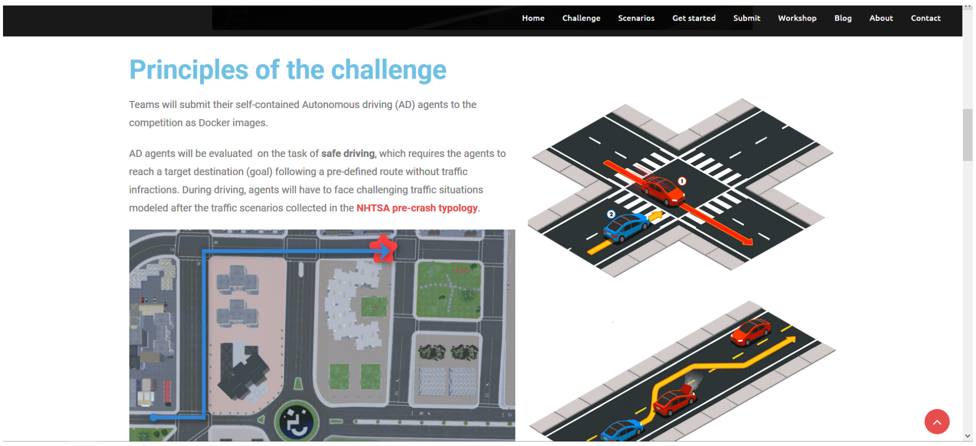

THANK YOU!