Real-Time Simulation Environment for Autonomous Vehicles in Highly Dynamic Driving Scenarios

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MathWorks Automotive Conference 2019, Stuttgart

About Roborace

Roborace is a development platform for algorithms powering self-driving cars

History

- Third FormulaE series → a support series called Roborace added
- Races on Formula E tracks
- Provides the first racing series for autonomous vehicles
- Teams taking part only develop the software for the provided autonomous Robocars
- The Human + Machine Challenge in 2018 in Berlin

Future

- 2019: 4 x competitions planned (Montebianco, Berlin, …)
- Several cars on one track

Video: Human + Machine Challenge 2018 in Berlin

Roborace: TUM Team Structure

Prof. Dr.-Ing.
Markus Lienkamp
Chair of Automotive Technology

Prof. Dr.-Ing.
Boris Lohmann
Chair of Automatic Control

Johannes
Betz

Alexander
Heilmeier

Alexander
Wischnewski

Tim Stahl

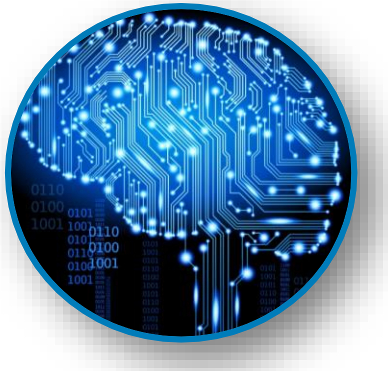
Leonhard
Hermansdorfer

Thomas
Herrmann

Felix Nobis

Roborace: Motivation for TUM

Know How:
- Artificial intelligence algorithms
- Sensor fusion
- Control
- Automotive technology



Road relevant research:
- Real traffic scenarios
- Static and dynamic objects
- Different road quality and road surfaces

Research:
- PhD thesis
- Publications
- Student thesis

Teaching:
- New lectures

Roborace & TUM: Milestones

- Software development started in January 2018
- Focus → reliable algorithms and rapid prototyping
- DevBot uses LIDAR and GPS to build the map in advance and localize
- Achieved 150 kph at ~80 % of the maximum friction level fully autonomously
- Collaboration with Speedgoat to enable Real-Time HIL set-up

Roborace: Vehicles

Development car Devbot
- Based on an LMP chassis
- Can be driven manually

Racing car Robocar
- Developed from scratch for fully autonomous racing
- Nearly all internal components are equivalent to DevBot

Both vehicles equipped with
- 5x LiDAR, 6x Camera, 2x RADAR, 17x Ultrasonic
- Optical Speed Sensor, Vehicle Dynamic Sensors
- 4x Electric motors
- 62 kWh Battery

Roborace: ECU Hardware Set-Up

Hardware

Nvidia Drive PX2

Mobile real-time target machine

Software

Perception → **Planning** → **Control**

Software Language

C++

ROS

python

MATLAB SIMULINK

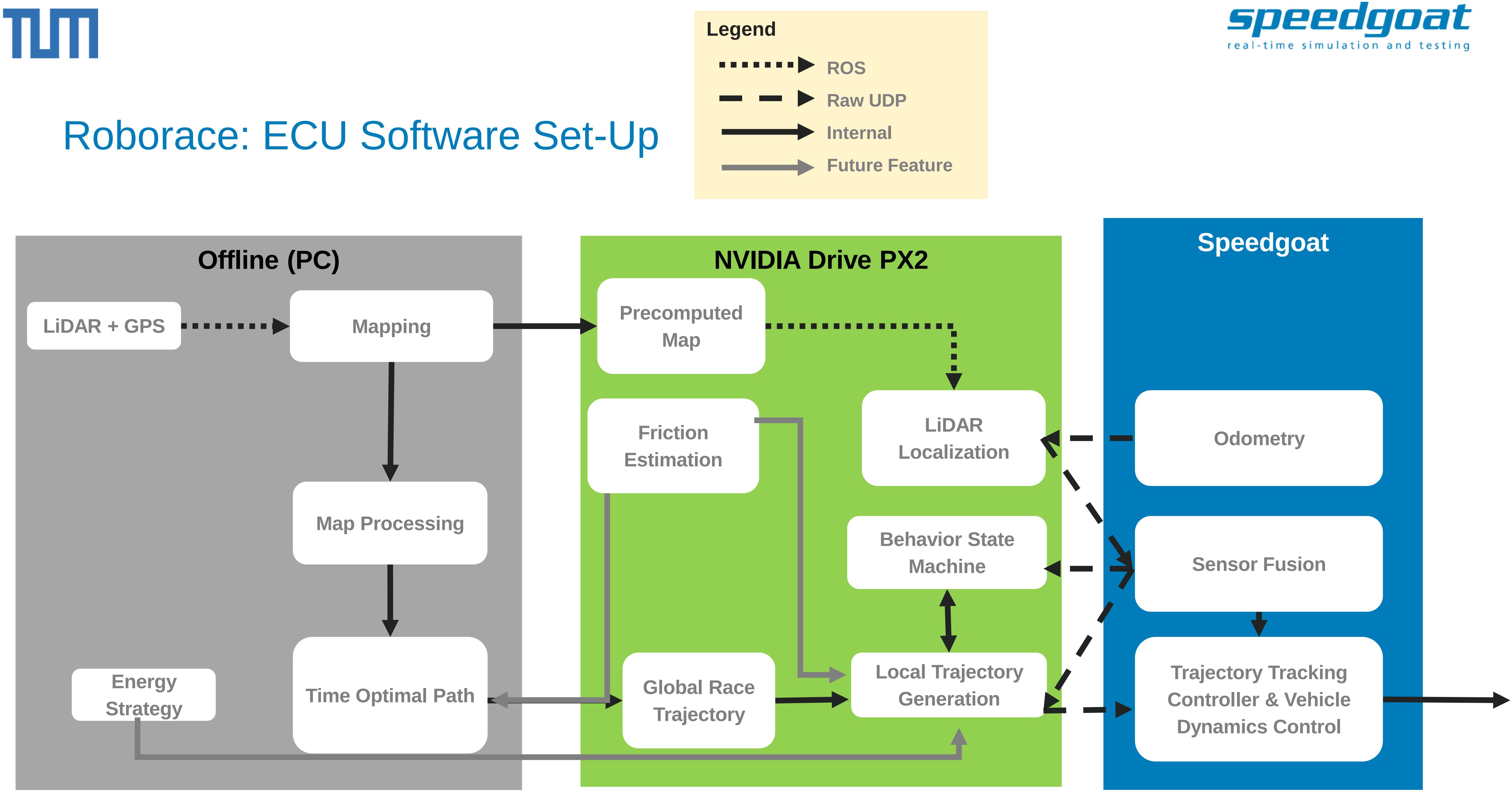
Interface

ØMQ

UDP

Ethernet

Roborace: ECU Software Set-Up



Testing & Validation

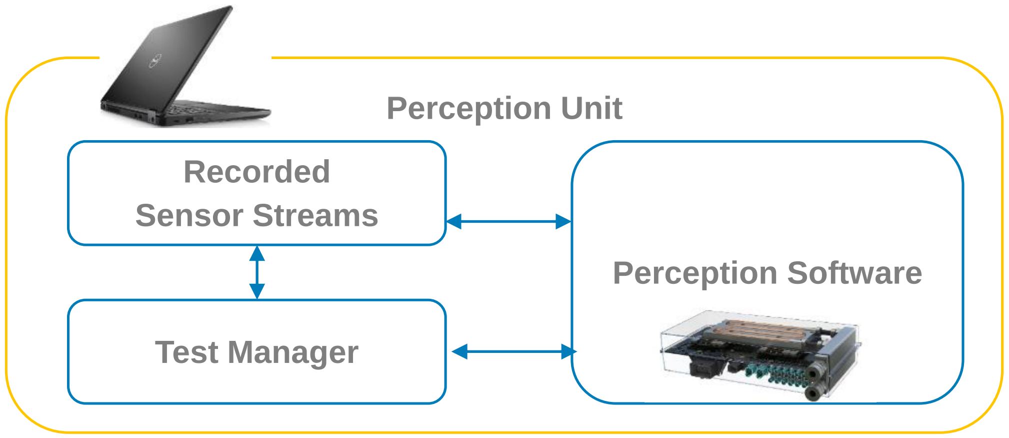
Due to limited testing time on track other means are required to test and validate functions such as:

- The inter-component communication
- Behavior on
  - Static/dynamic obstacles
  - Safety/emergency stops
  - Sensor failures
- Identify performance potentials regarding
  - Processor loads
  - Parametrization of algorithms with realistic noise
- Train startup-logic and evaluate working procedures

Software Module Testing

Perception Unit (NVIDIA Drive PX2)

- Use pre-recorded LIDAR data to test
- Check mapping and localization algorithms
- Check interfaces using NVIDIA Drive PX2



Perception Unit

Recorded Sensor Streams

Test Manager

Perception Software

Control Unit (later: Mobile Real-Time Target Machine by Speedgoat)

- Control software simulated in Simulink
- Same interfaces to vehicle model as in real car
- Driven by replaying recorded trajectories

Control Unit

Recorded Trajectories

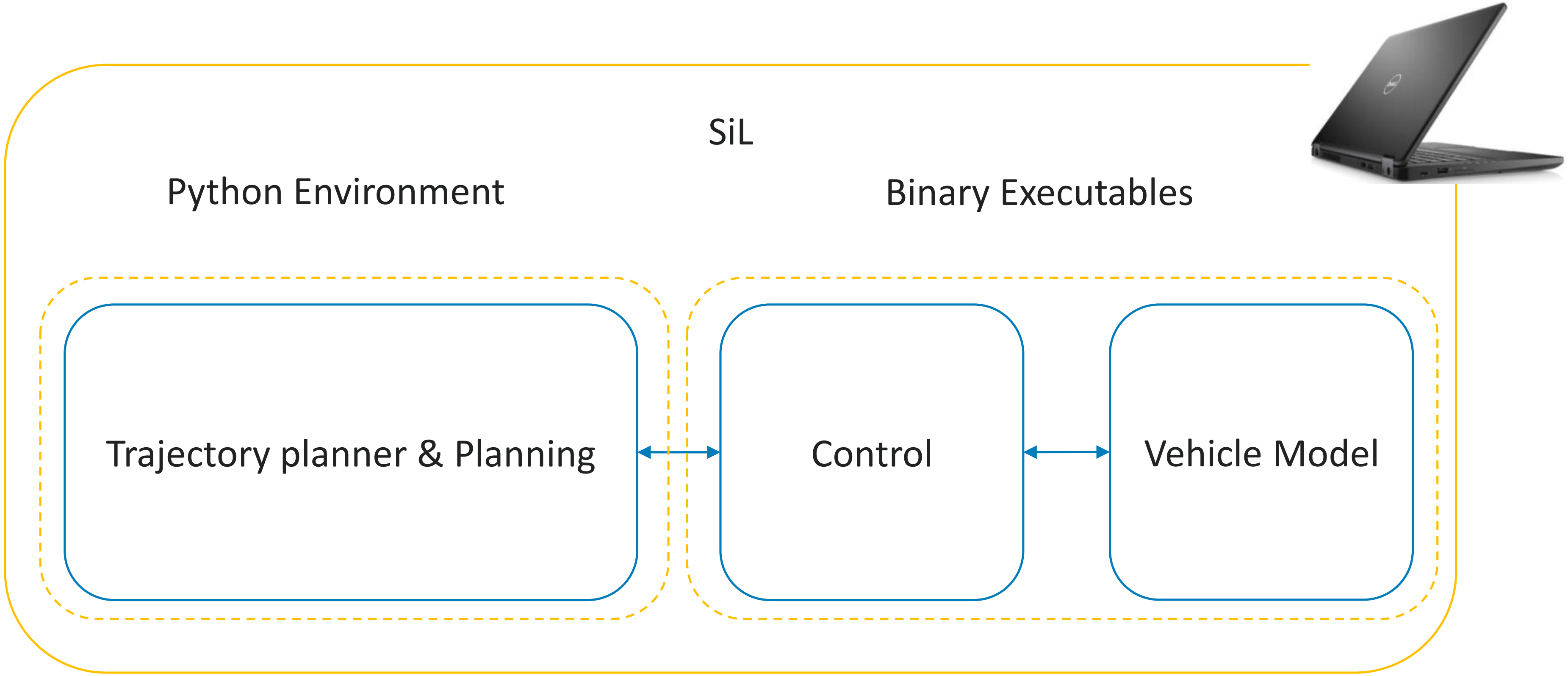
Control

Vehicle Model

Software Module Testing

Software-in-the-Loop

Communication realized via same interface as in real car (UDP)



Limitations & Challenges of Current Testing Methods

- Testing on track:
  - Track-time is very limited
  - Covering all safety relevant scenarios difficult
  - Testing algorithms in safe environment is key
  - Inconvenient debugging

- Testing using recorded data from previous runs
  - Interaction between vehicle and changes in the algorithms not testable
  - Limited variety of test scenarios implementable

- Transfer of research to generic AD- and ADAS application development

Using a HIL System to Simulate the Vehicle & Environment

- Closed-loop testing in virtual environment
  - Test interaction between the real ECU and vehicle already in the lab
  - Test safety relevant functions in the virtual environment first
  - Generate dynamic sensor realistic feedback to test algorithms

- Real-time HIL system required that can
  - Run vehicle & low-level ECU models in real-time & deterministic
  - Communicate with the ECU using the same interfaces
  - Simulate the environment and various sensor feedbacks to interact with ECU

- Ideally: spend as little time as possible on model adaption and code deployment
- Solution: Speedgoat real-time systems & Simulink Real-Time!

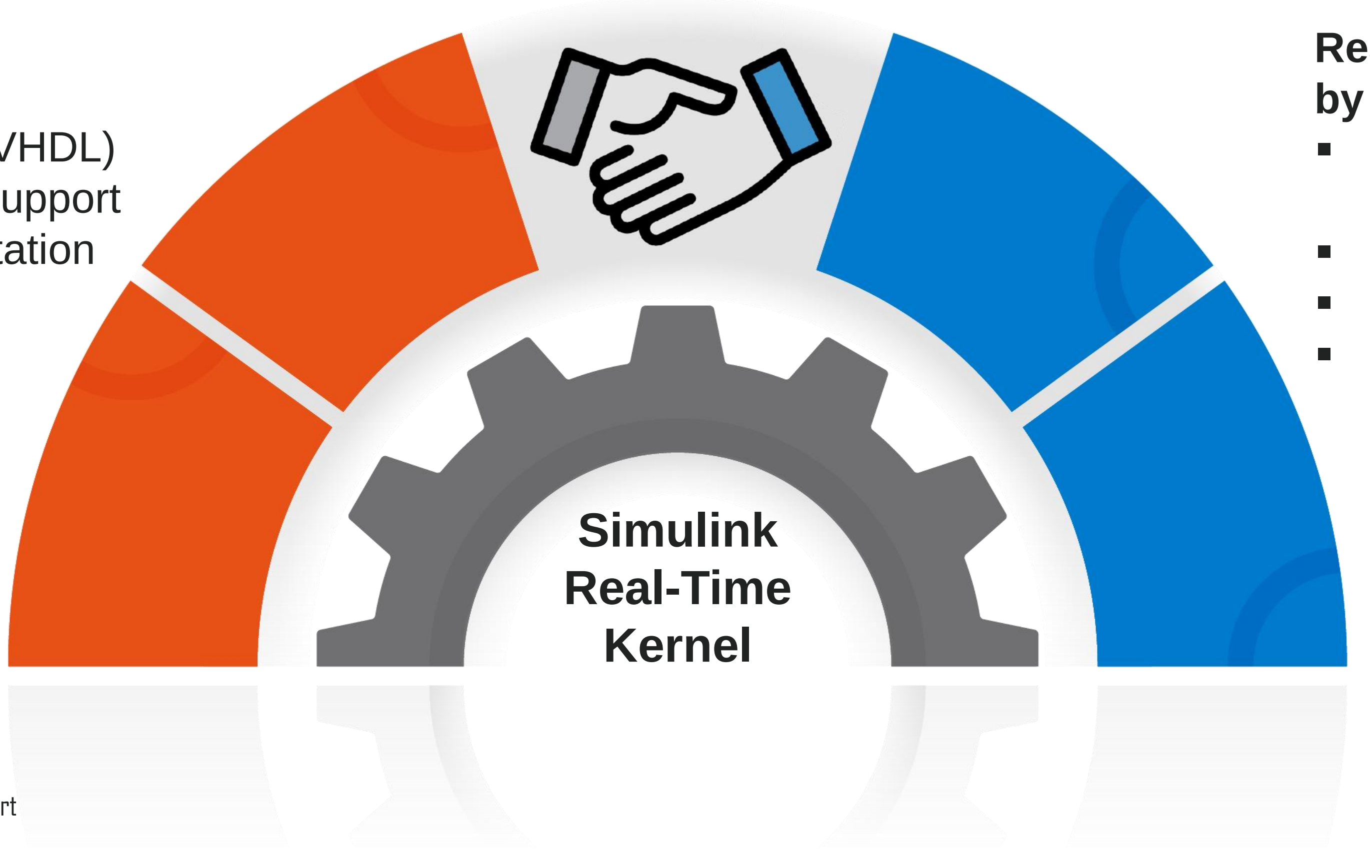
About Speedgoat

- Real-time solutions designed specifically to work with Simulink
- A MathWorks associate company
- Incorporated in 2006 by former MathWorks employees in Switzerland
- Headquarter in Switzerland with subsidiaries in the USA and Germany
- Real-time core team of around 100 people within MathWorks and Speedgoat
- Working closely with the entire MathWorks organization worldwide and its over 4000 employees

How it Works
Real-Time Simulation and Testing

Simulink Real-Time by MathWorks

- Code Generation (C/VHDL)
- Toolboxes/Blockset Support
- Real-Time Instrumentation
- Simulink Test



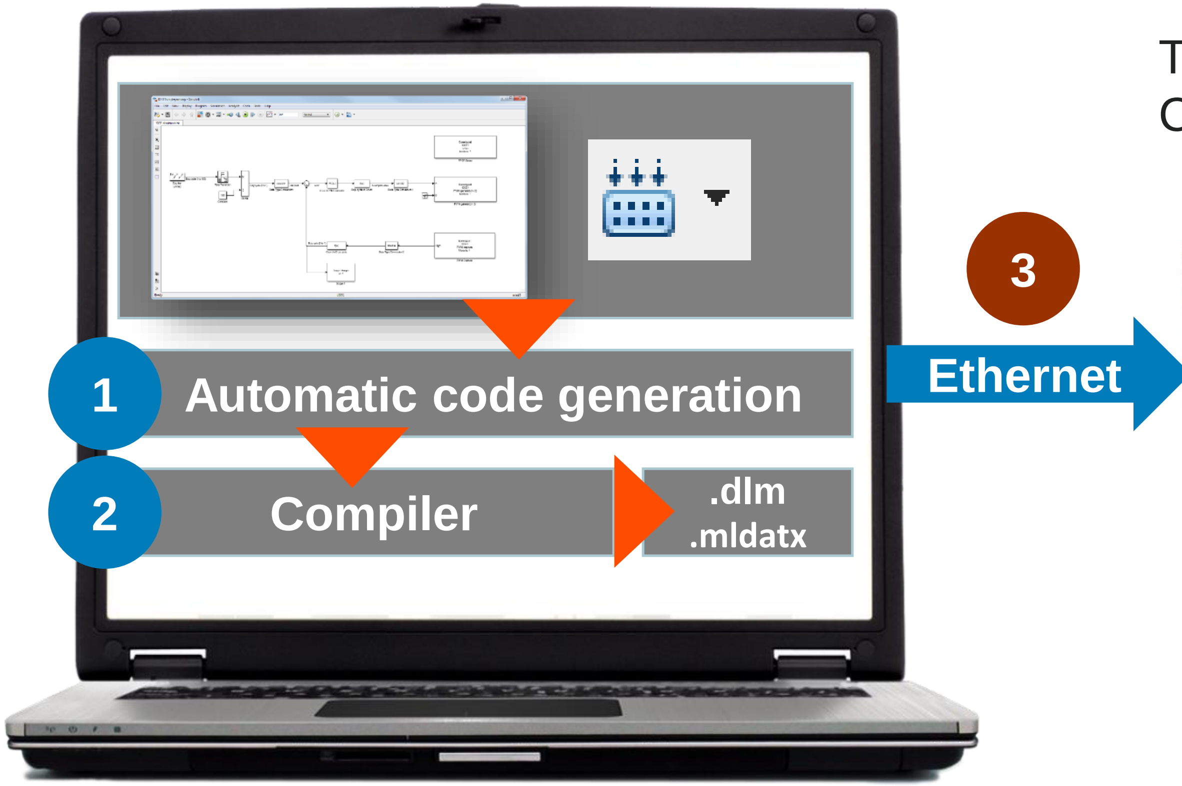
Real-Time Target Machines by Speedgoat

- I/O modules / protocol support
- FPGA-based solutions
- Speedgoat driver library
- Complete hardware-in-the-loop rigs

Fast-Track from Desktop to Real-Time Simulation and Testing

Automatically create your real-time application from Simulink

1. Automatic C or VHDL Code Generation
2. Compile and Synthesize
3. Download and Ready to Run



Target machine with multicore CPU, FPGAs, and I/O

"With limited resources as a start-up, the time to get things working is really key. Speedgoat excelled for us." -- *ClearMotion*

Speedgoat Real-Time Systems Ideal for Automotive Applications

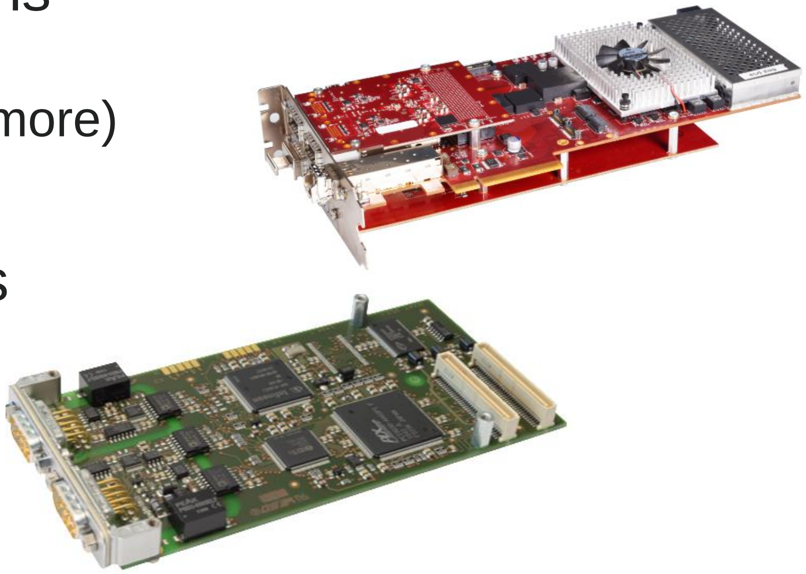
- Different real-time systems to meet your requirements:
  - Mobile: Performance System ideal for in-vehicle use
  - Performance: High Performance for most demanding most demanding applications
  - Complete Racks: Customized to your specific requirements!

Speedgoat Real-Time Systems: Ideal for Automotive Applications

- I/O connectivity and communication protocols support:
  - Vehicle communication (CAN, CAN-FD, LIN, J1939, FlexRay, PSI5 and many more)
  - HIL testing platform for battery management systems
  - ….

- High-performance FPGAs for most demanding applications
  - HDL coder support
  - FPGA code module support (CAM, CRANK, PWM and many more)

- Seamless integration of Simulink toolboxes and blocksets
  - Vehicle Dynamics Blockset
  - Simscape
  - Powertrain Blockset
  - …



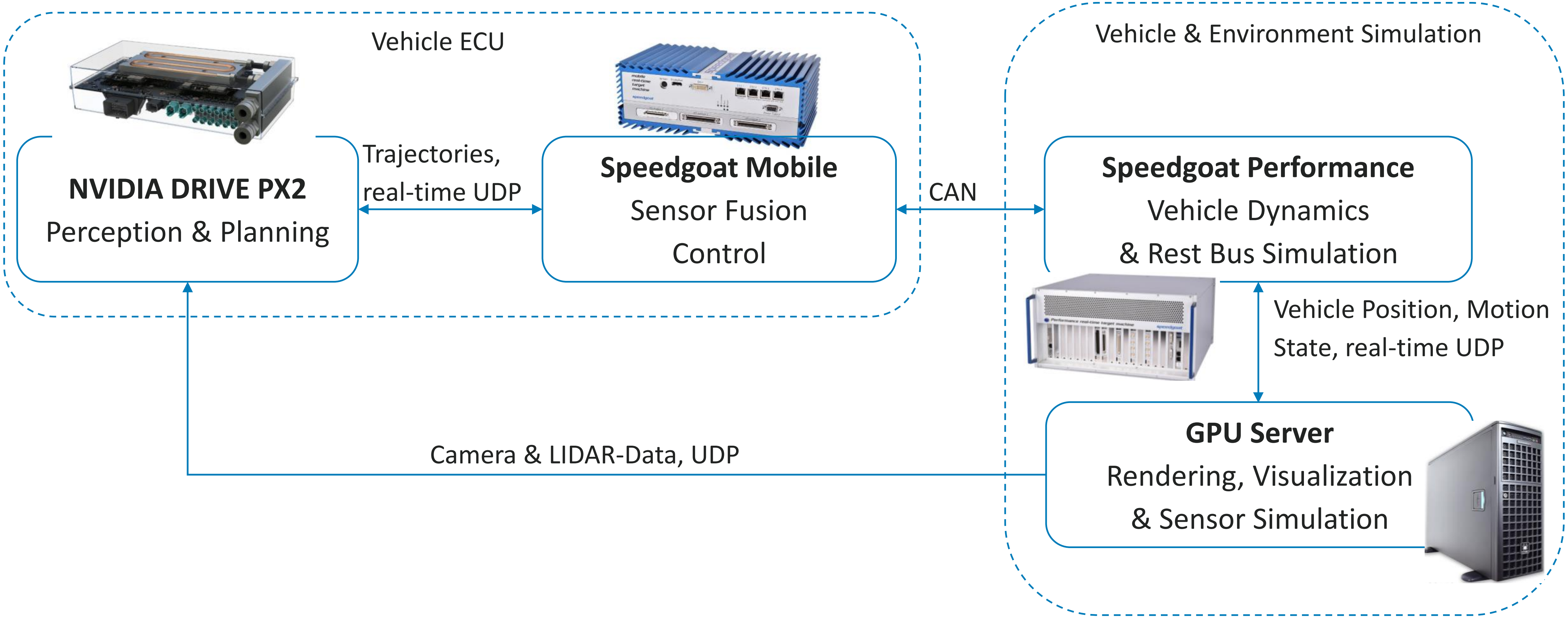
Speedgoat Real-Time Systems: Fast Track Your Development!

Lots of customers already rely on Speedgoat systems to fast track their development efforts regarding:

- Automated Driving ADAS
- Electrification
- Battery Management Systems
- Engine & Drivetrains
- Drive-By-Wire

Visit Us at our booth “To be defined”

Code Integration Workflow - HIL



Vehicle ECU

NVIDIA DRIVE PX2
Perception & Planning

Trajectories,
real-time UDP

Speedgoat Mobile
Sensor Fusion
Control

CAN

Vehicle & Environment Simulation

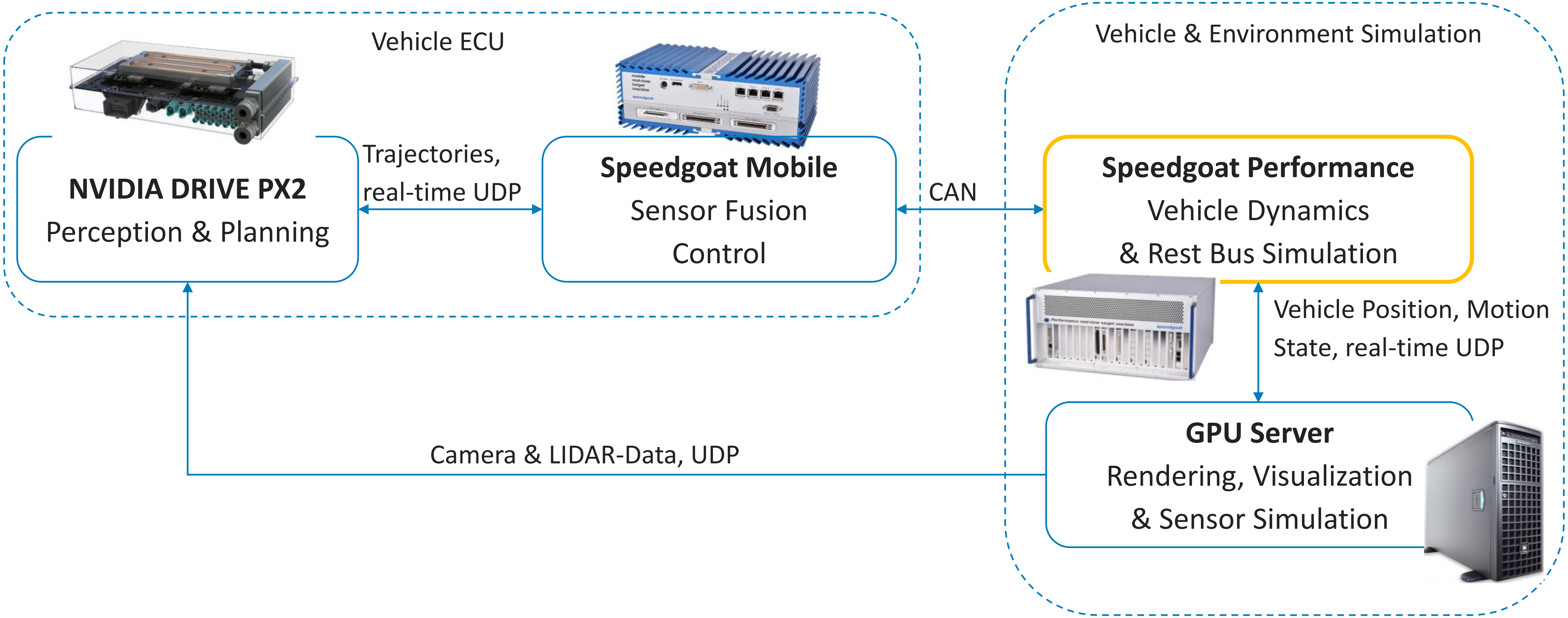
Speedgoat Performance
Vehicle Dynamics
& Rest Bus Simulation

Vehicle Position, Motion
State, real-time UDP

GPU Server
Rendering, Visualization
& Sensor Simulation

Camera & LIDAR-Data, UDP

Code Integration Workflow - HIL



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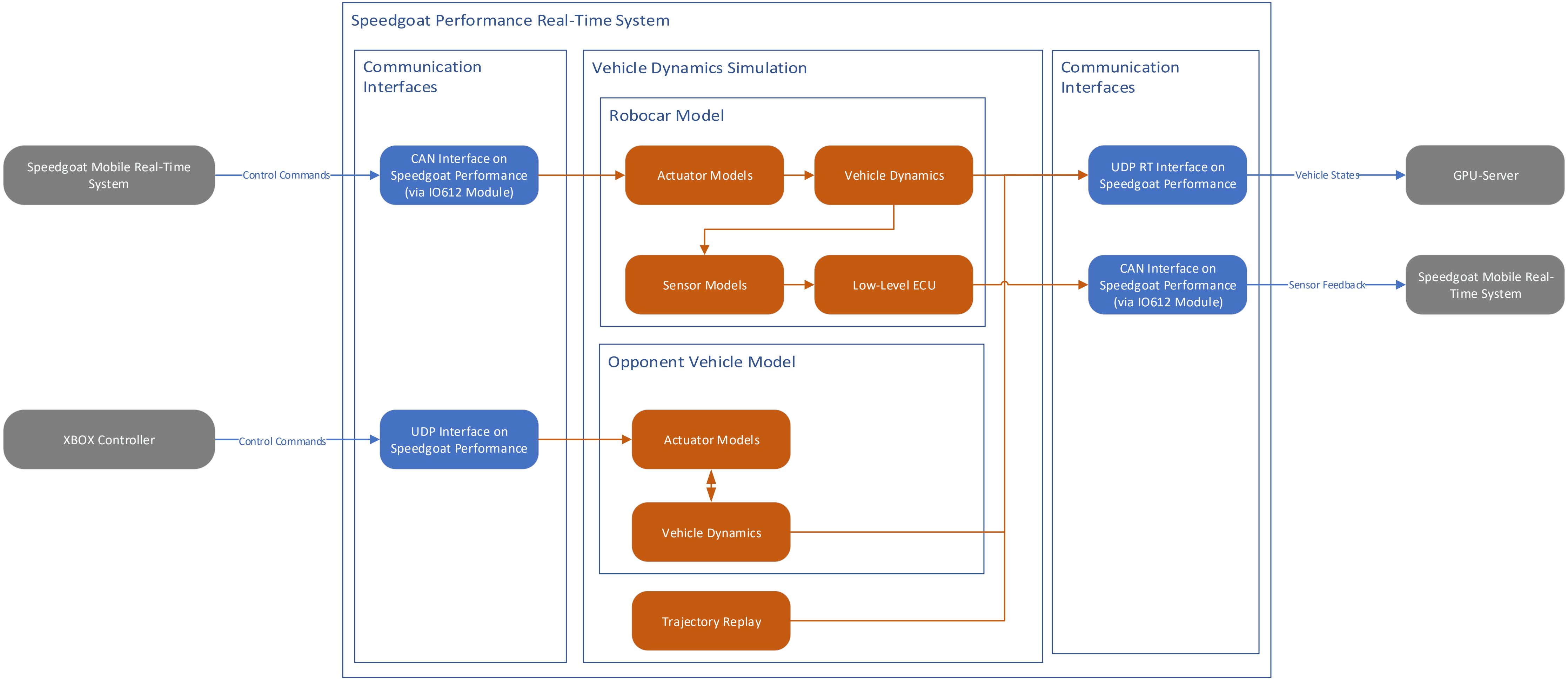
Vehicle Dynamics & Rest-Bus Simulation

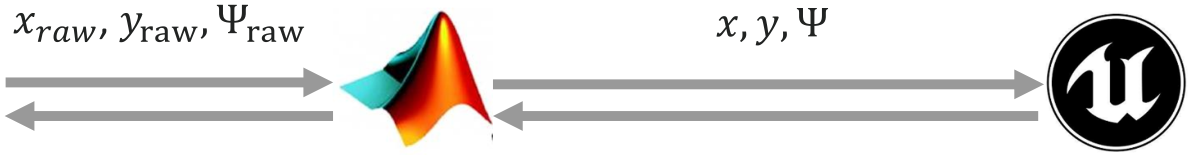


Communication Between Simulink and Unreal Engine Using the Vehicle Dynamics Blockset

- Input:
  - position (x, y-coordinates) & heading Ψ from vehicle-simulation or
  - manual steering mode

- Output:
  - Camera stream
  - LIDAR-stream

- Vehicle Dynamics Blockset allows to interface with Unreal-Engine easily



$x_{raw}, y_{\mathrm{raw}}, \Psi_{\mathrm{raw}}$

x, y, Ψ

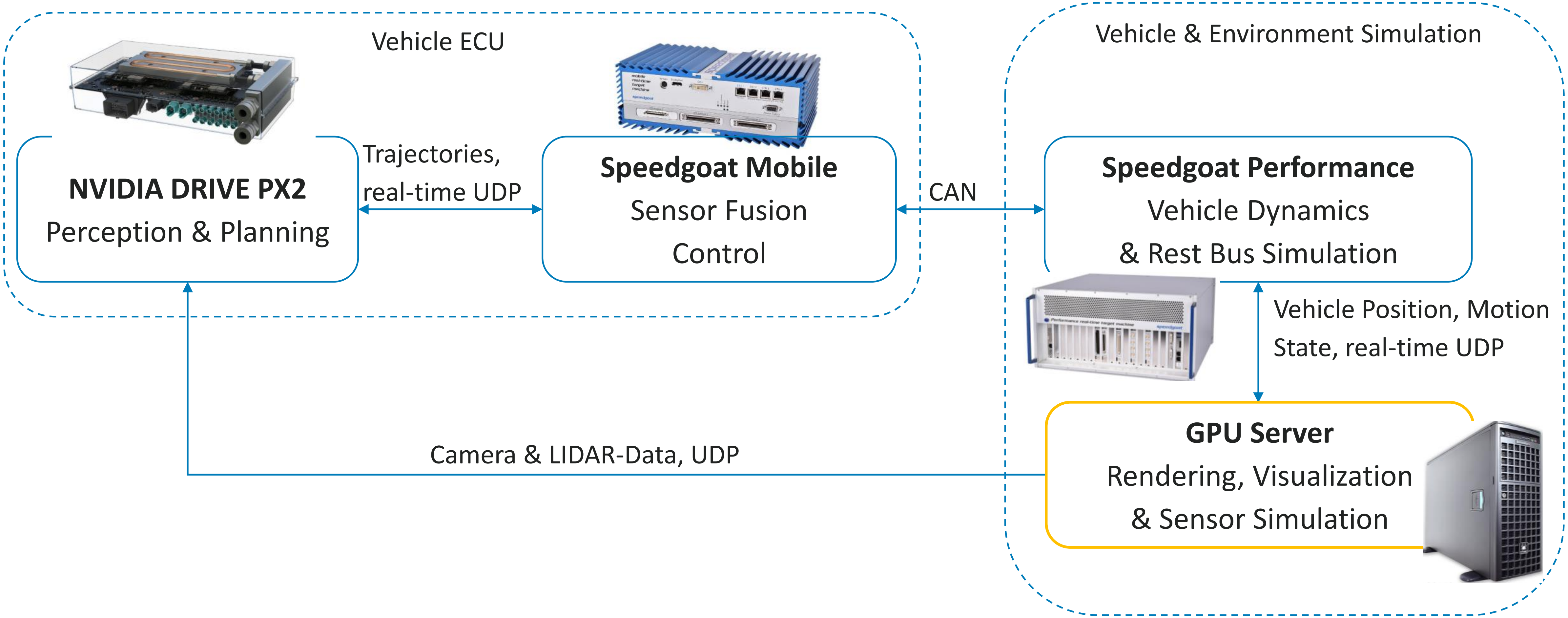
Camera stream,
LIDAR to ROS

Rx-model

Camera stream,
LIDAR

Visualization

Code Integration Workflow - HIL



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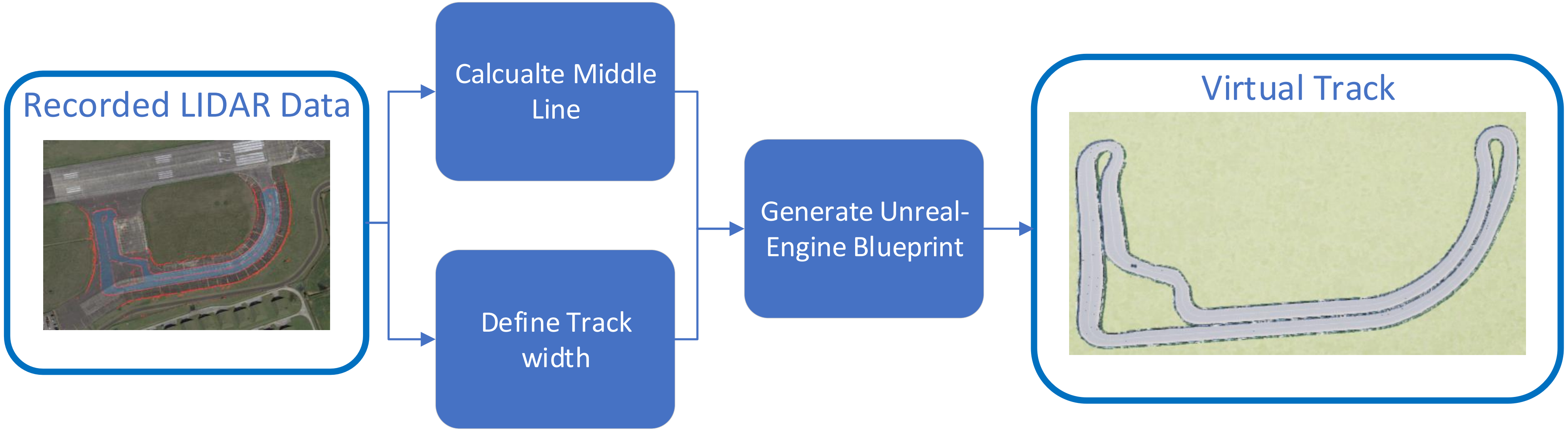
Unreal-Engine: Creating Tracks with Recorded Data

- Re-building real-tracks in virtual world fast and easy



Recorded LIDAR Data

Calcualte Middle Line

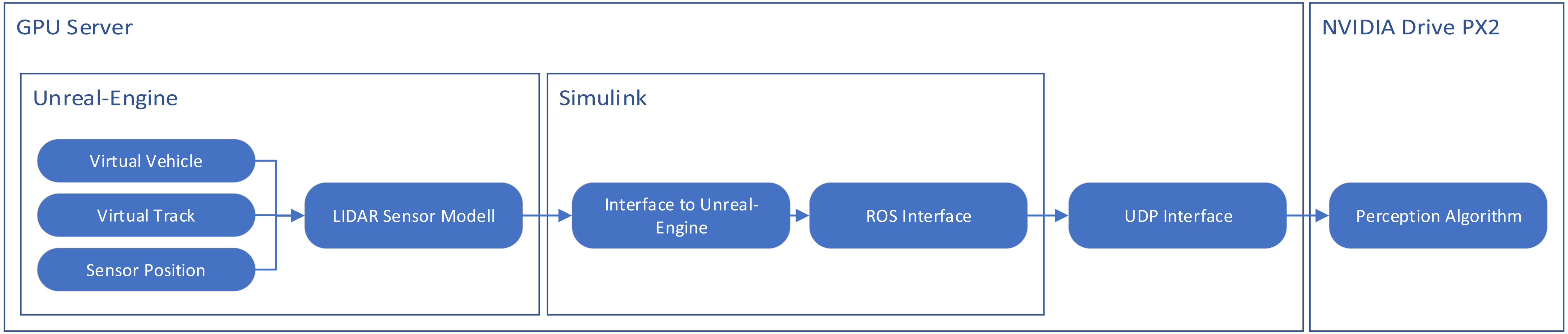
Define Track width

Generate Unreal-Engine Blueprint

Virtual Track

Unreal-Engine: Virtual Car & Virtual Sensors

- Sensor Models from MathWorks allow realistic closed-loop testing



GPU Server

Unreal-Engine

Virtual Vehicle

Virtual Track

Sensor Position

LIDAR Sensor Modell

Simulink

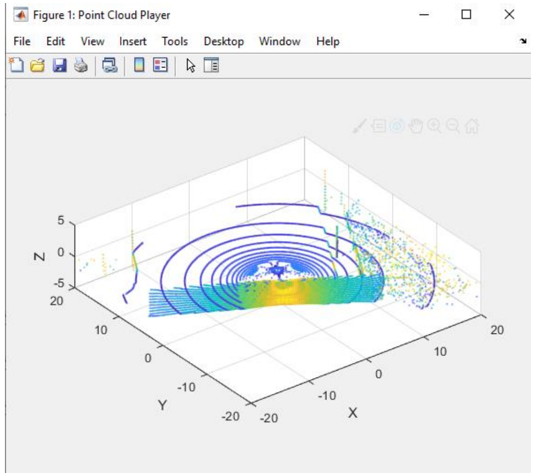
Interface to Unreal-Engine

ROS Interface

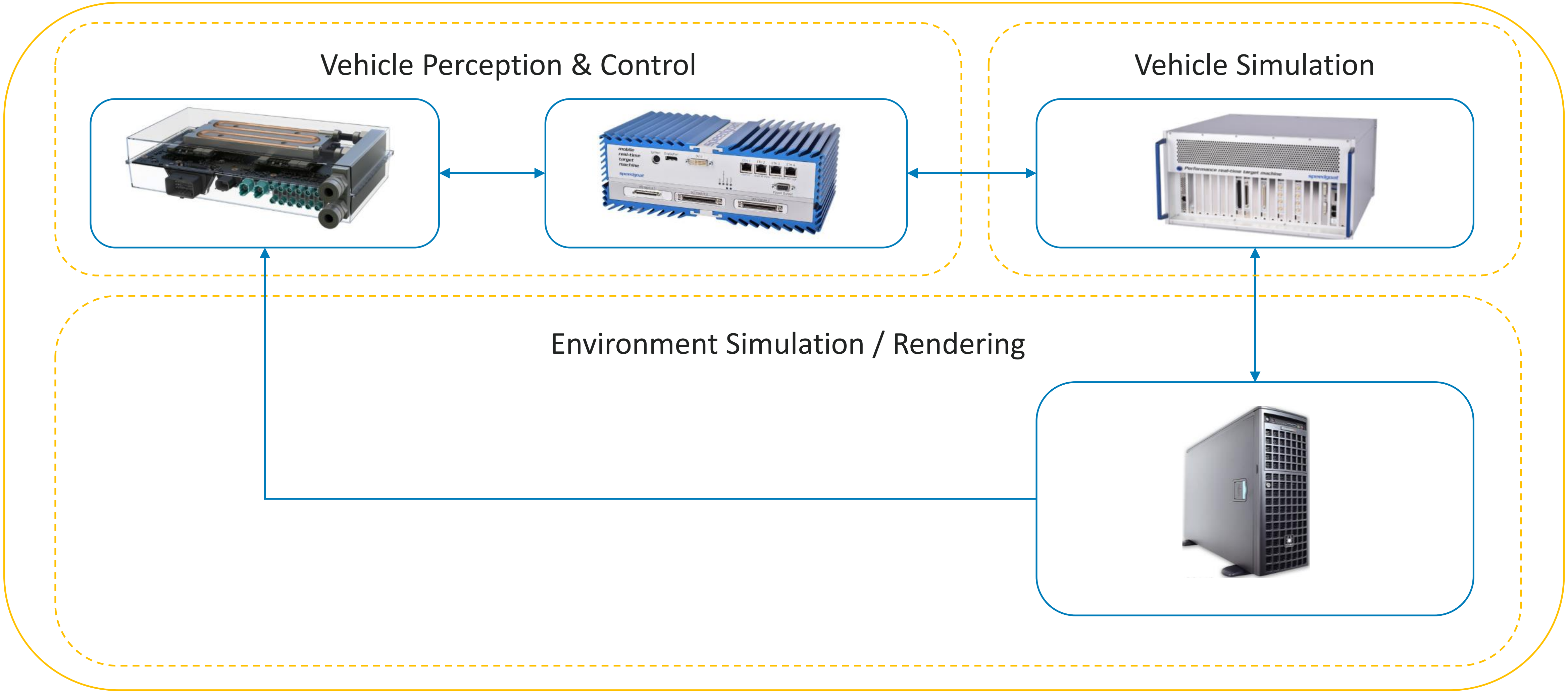
UDP Interface

NVIDIA Drive PX2

Perception Algorithm



Code Integration Workflow - HIL



Vehicle Perception & Control

Vehicle Simulation

Environment Simulation / Rendering

Conclusion

- Presented HIL set-up
  - Allows extensive testing & training in-house
  - Seamless Workflow provided by using Speedgoat Systems with Simulink Real-Time
    - Minimizes time spent for configuration
    - Maximizes time spent on algorithmic development

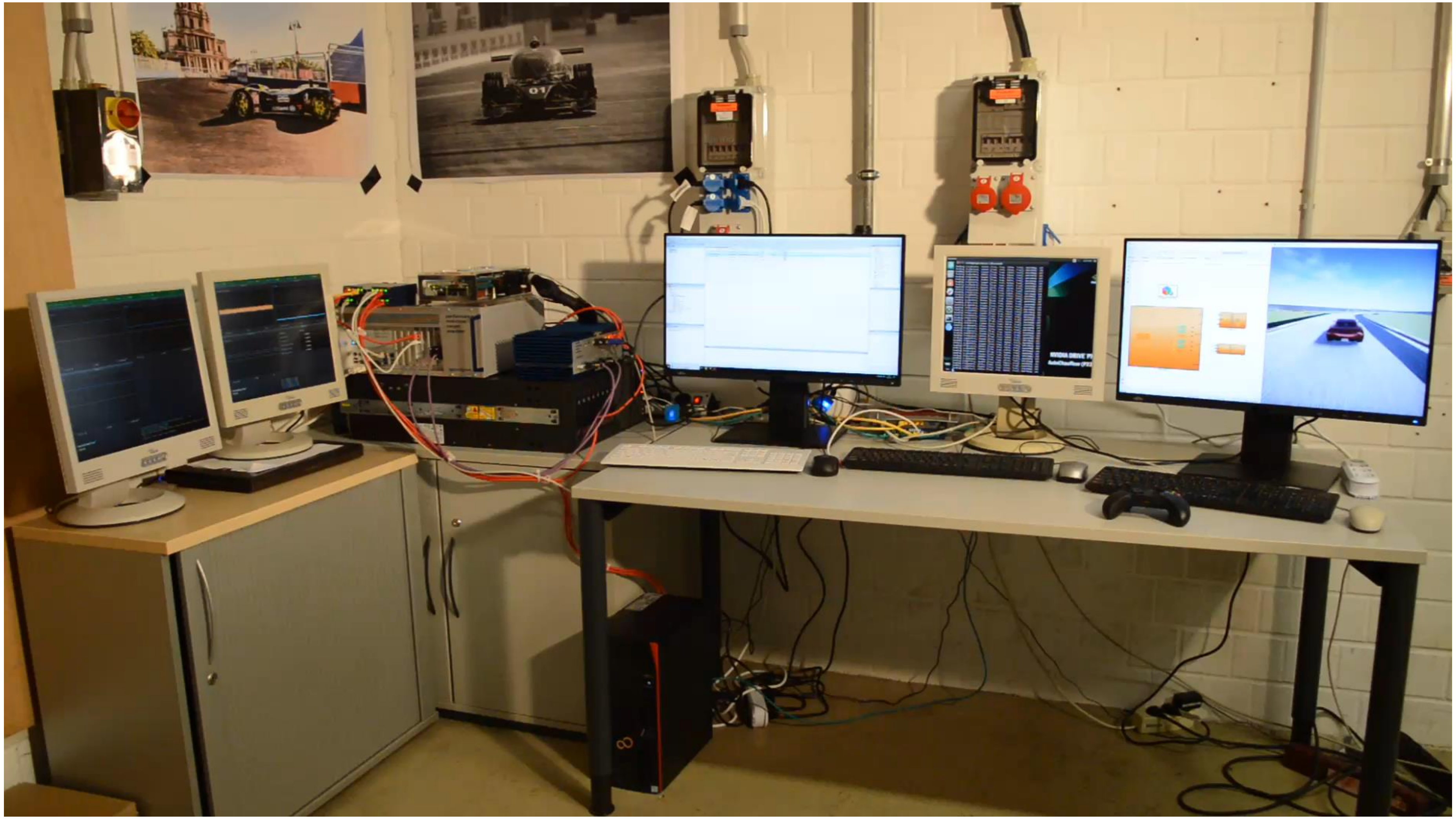
Next Steps Situation

- Preparing for race events in Spain and Germany
  - Leverage HIL set-up to train & test algorithms extensively before going to track

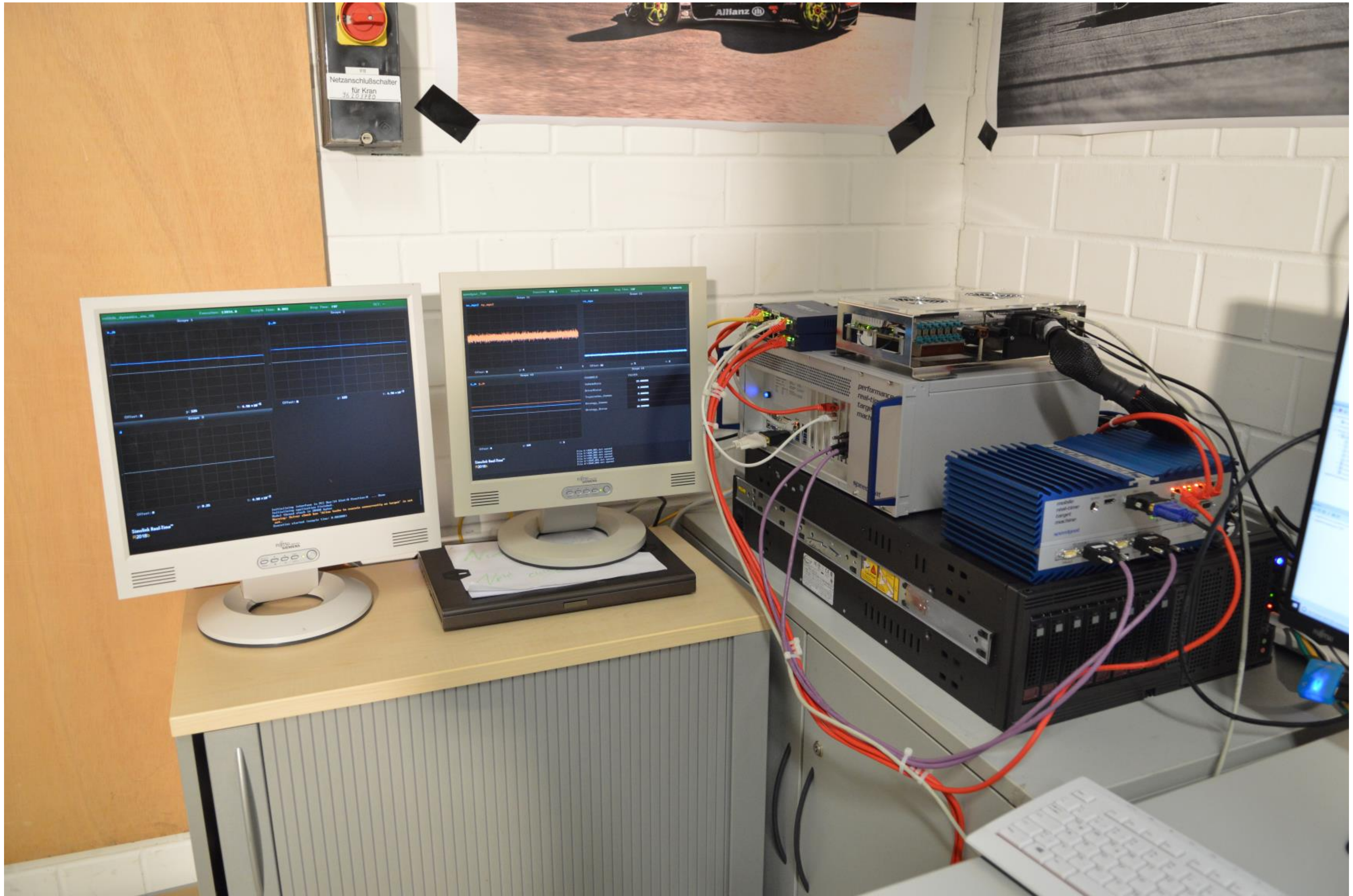
Future

- Open-source more of our software modules (link)
- Make HiL accessible to community
- More features in software stack for autonomous driving applications
- Integrate Speedgoat Baseline on self-developed 1:10 model cars

HiL @ TUM



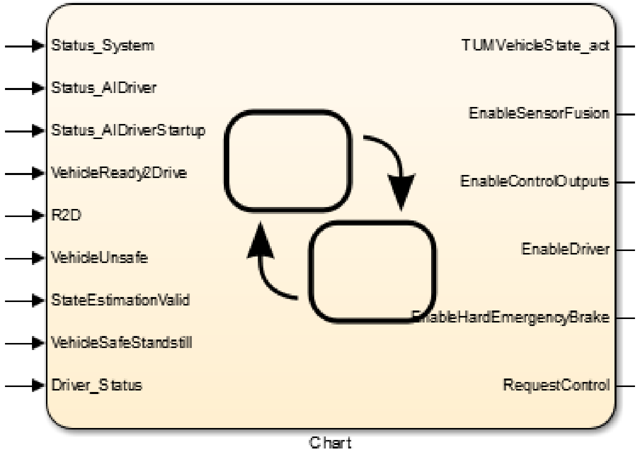
Backup

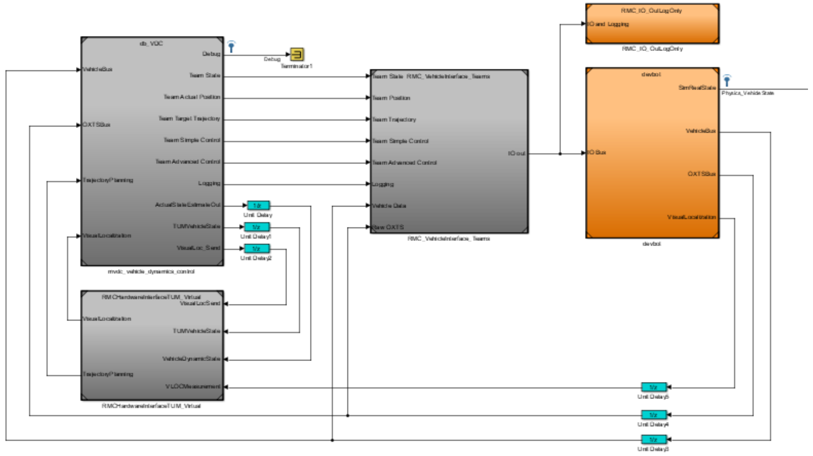


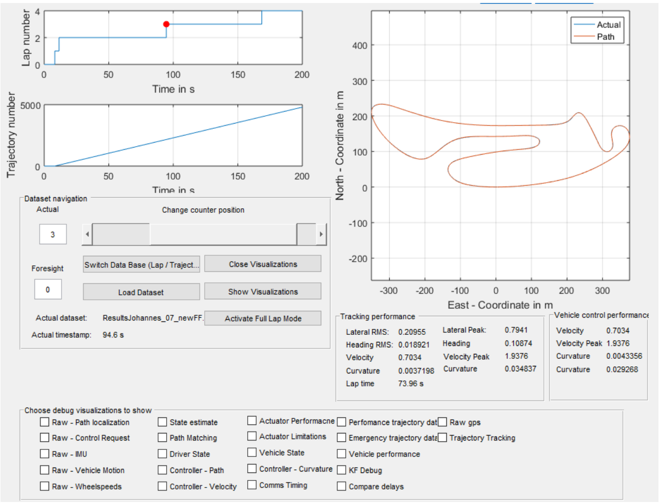
Backup

Mathworks Software in the Project

- Function development
    - Speed control
    - Path tracking control
    - Sensor fusion
    - Vehicle state machine
    - More to come..
- Simulation
    - Software in the loop simulation
    - Self-designed vehicle dynamics
    - Real-Time testing
- Project organization
    - Simulink Project
    - Referenced models
    - Data dictionaries
    - Simulink Test
    - Data analysis
    - Merge tools (git)







Actual: 3

Foresight: 0

Actual dataset: ResultsJohannes_07_newFF.

Actual timestamp: 94.6 s

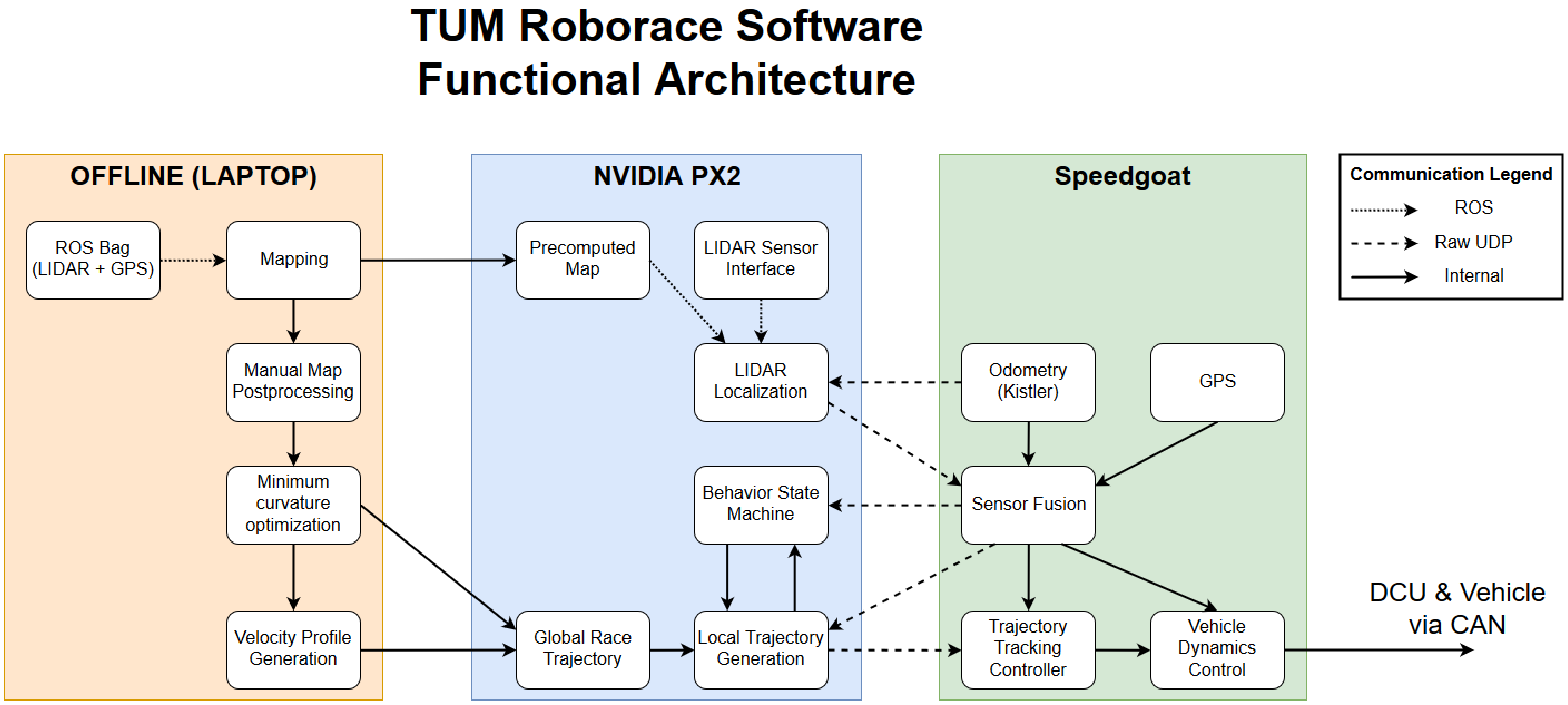
Tracking performance

Lateral RMS:	0.20955	Lateral Peak:	0.7941
Heading RMS:	0.018921	Heading	0.10874
Velocity	0.7034	Velocity Peak	1.9376
Curvature	0.0037198	Curvature	0.034837
Lap time	73.96 s		

Vehicle control performance

Velocity	0.7034
Velocity Peak	1.9376
Curvature	0.0043356
Curvature	0.029268

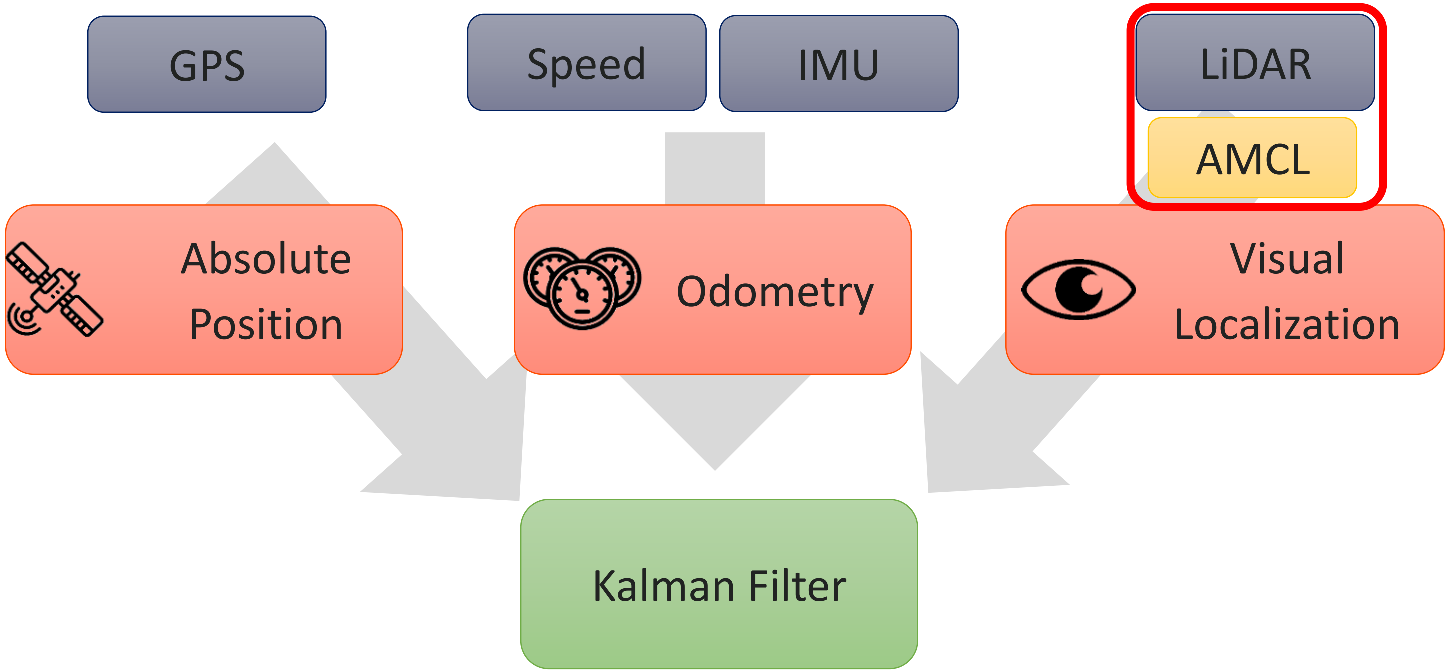
Software Architecture – General Design



TUM Roborace Software Functional Architecture

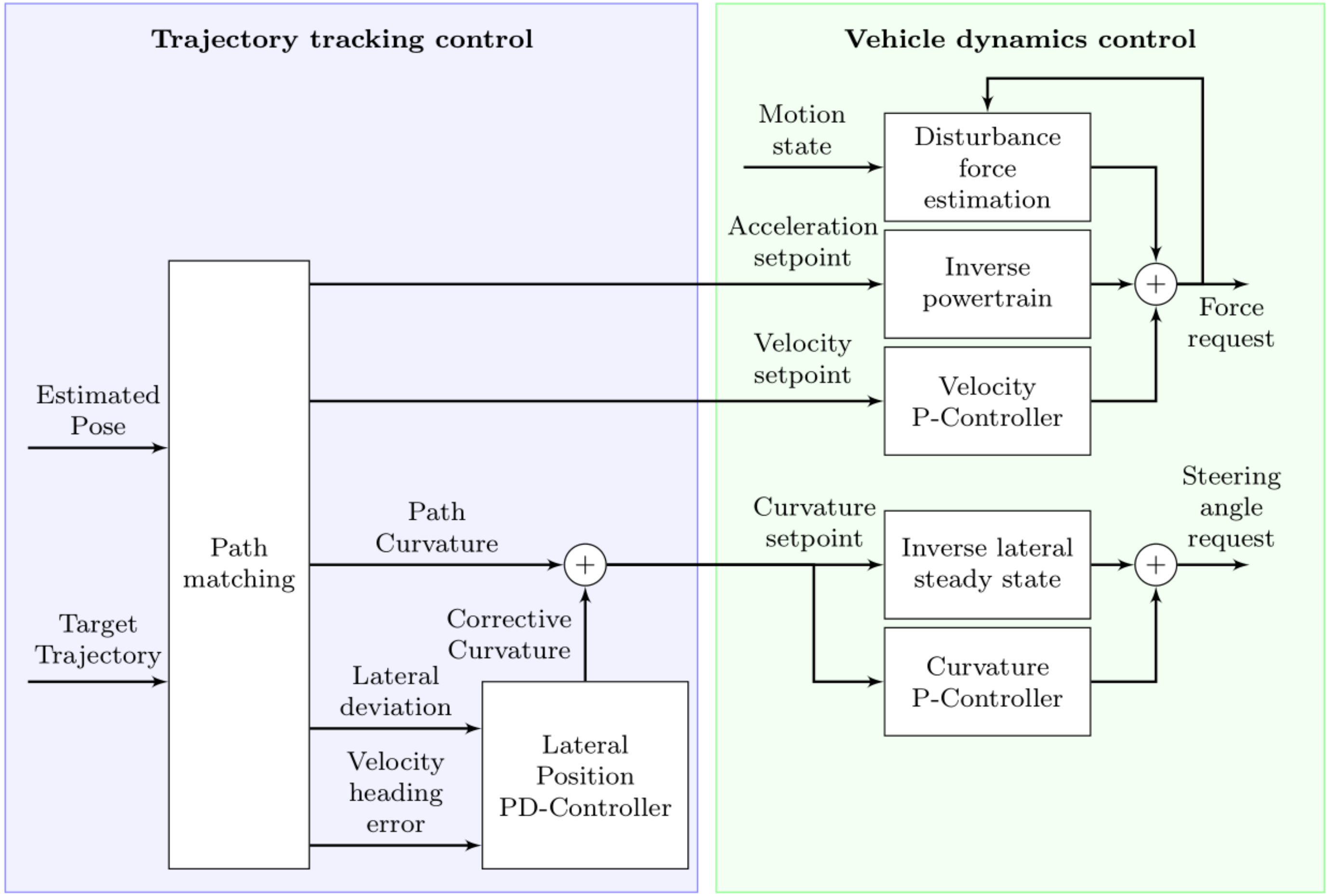
Software Functionality – Localization

- Application of AMCL (Adaptive Monte Carlo Localization)
- Odometry based on optical velocity sensor
- Fusion with GPS in a second step



Software Functionality – Control

- Feedback control of lateral deviation and velocity error
- Tuning is difficult for high speed > 130 kph
- No integral action in lateral feedback path to prevent difficulties in chicanes



Tracking and Prediction of Traffic Participants

Problem/Motivation

- Many traffic collisions arise through human error
- Make the car aware of its surroundings through sensor technologies

Goals

- Efficiently detect, track and predict the behavior of traffic participants (cars, bicycles, pedestrians)
- Enable the generation of a trajectory for the ego vehicle which takes into account the knowledge of its surroundings to avoid accidents

Approach

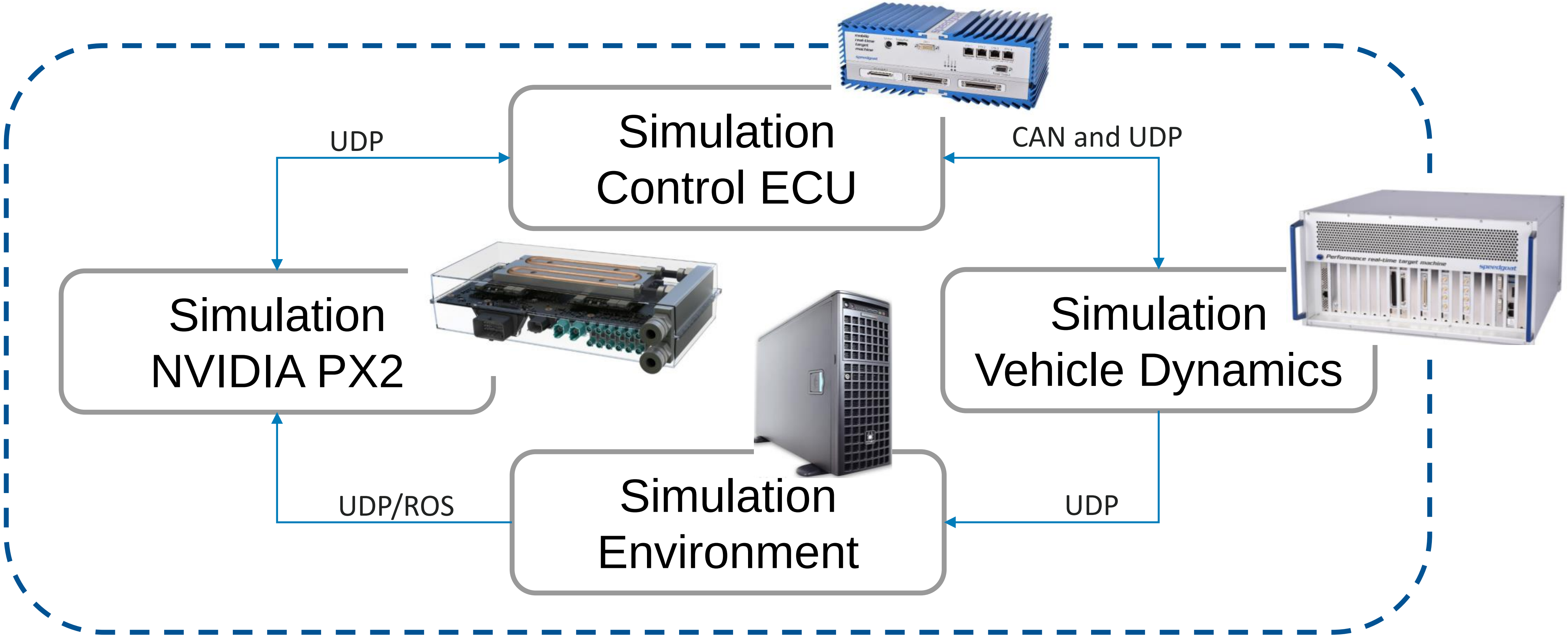
- Estimate movement possibilities for different object classes through classification
- Evaluate machine learning approaches for detection and prediction

- http://safecarnews.com/wp-content/uploads/2016/01/Conti-UK-1.jpg

- https://blogs.nvidia.com/wp-content/uploads/2016/01/ces-computer-vision-example-web.gif

Simulation – Hardware from Speedgoat

- **Mobile real-time target machine** → Fast control dynamics, used vehicle ECU
- **Performance real-time target machine** → Fast sensor sample rates, no delay and complex scenarios possible



Simulation Control ECU

Simulation NVIDIA PX2

Simulation Vehicle Dynamics

Simulation Environment

UDP

CAN and UDP

UDP/ROS

UDP

Safety Assessment of an Autonomous Roborace Race Vehicle

Problem/Motivation

- Artificial intelligence (AI) for safety critical tasks in autonomous driving (e.g. trajectory generation)
- Due to the non-deterministic nature of AI, a proper and safe function can not be guaranteed

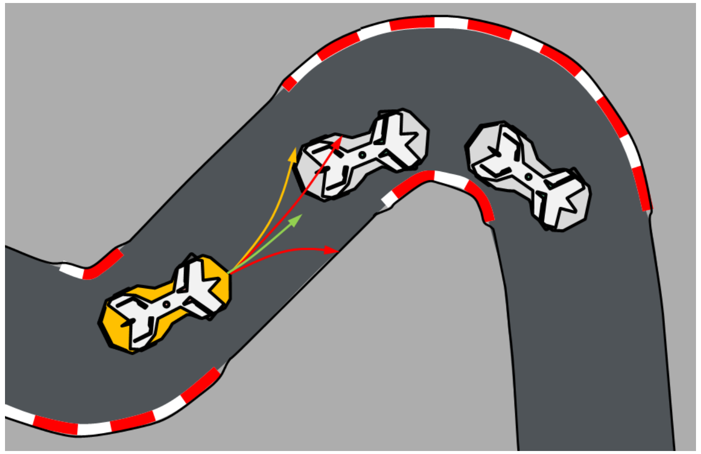
Goals

- Safety assessment of trajectories generated by non-deterministic approaches
- Application on an autonomous race vehicle (Roborace)

Approach

- Determination of features indicating a safe planned trajectory
- Development of a deterministic safety supervisor for race vehicles
- Implementation and evaluation of the supervisor on an Roborace vehicle

- Robocar [www.roborace.com/media/]



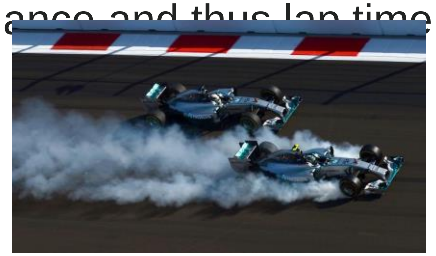
- Safety Assessment of Planned Trajectories

Estimation and Prediction of Tire Road Friction Potential

Problem/Motivation

- Tire road friction potential has a major impact on vehicle safety and on vehicle performance and thus lap time in racing scenarios
- The tire road friction potential depends on a huge variety of influencing factors

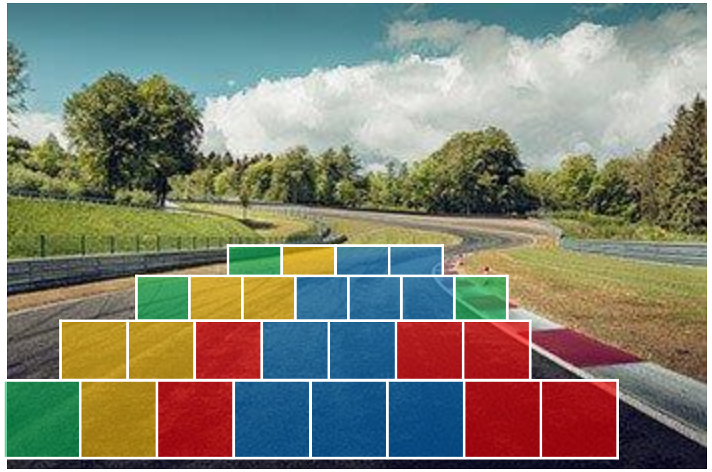
→ Knowledge of friction potential is essential for racing and autonomous driving



www.formula1.com/en/latest/features/2015/10/the-russian-grand-prix---did-you-know-.html

Goals

- Precise estimation of tire road friction potential and generation of a grid map
- Continuous updating of the ‚road friction map‘
- Prediction of tire road friction potential for short and long term (track section ahead and racetrack during whole race)



Approach

- Established methods relying on vehicle sensors, vehicle dynamic model, tire model, …
- Utilizing machine learning techniques with focus on
  - camera based friction estimation / prediction
  - Tire model-less tire force calculation
  - friction estimation based on acoustics

Safe Learning Control for Autonomous Vehicles

Motivation

- Classic control approaches depend heavily on model quality
- Difficult to deal with tire wear, low level component changes and changing environment conditions

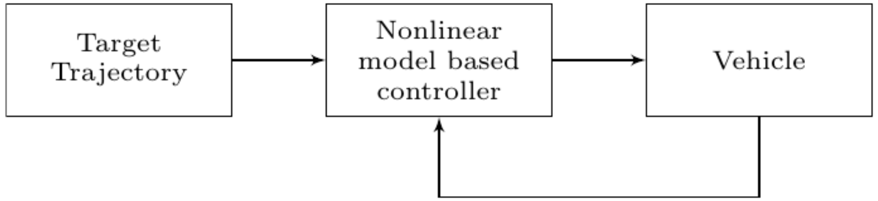
→ Works well until 70-80% of the available friction

Goals

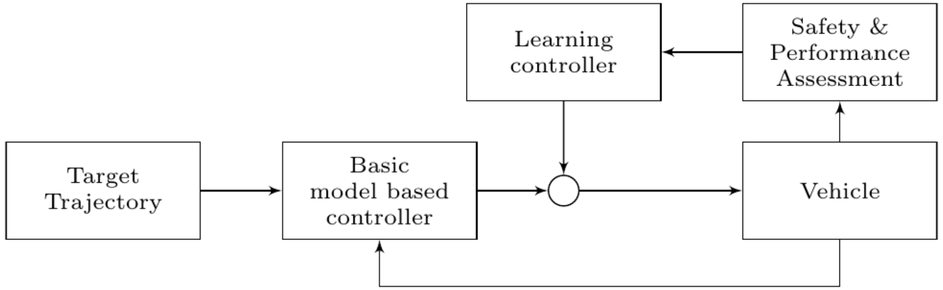
- Develop an algorithm which is capable of approaching the handling limit slowly and with care
- Guarantee safety and intuitive tuning of the algorithm

Approach

- Humans use a combination of experience and gut-feeling
- Use Machine Learning methods in combination with classic control theory to mimic this behavior
- Model the human safety and performance assessment for feedback (trajectory planning and learning style)



Commonly used concept for autonomous vehicle control



Integration of learning methods to relax quality requirements for nonlinear vehicle model while maintaining safety

Energy Management Strategy for Autonomous Electric Cars

Motivation

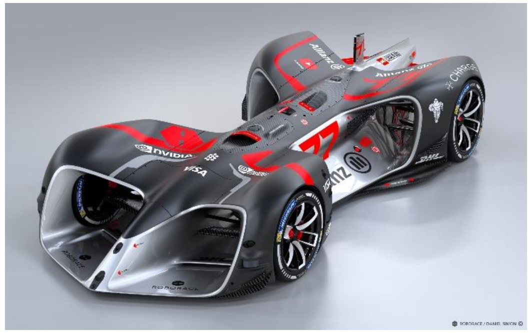
- Amount of stored energy in battery electric vehicles is limited
- Technical limitations of electric vehicles‘ components are reached soon due to highly dynamic driving scenarios

Goal

- Development of an Energy-Management-Strategy that optimizes the race trajectory and controls the power flow within the electric race car in real-time to optimize lap times for a whole race

Approach

- Deduction of controlling policies resulting from machine learning methods and comparison with conventional ones
- Development of an efficient operational strategy for an autonomous electric race car



https://roborace.com/media/