INTO-CPS

Industrial Results using INTO-CPS

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With valuable input from industrial partners

AARHUS UNIVERSITET
UNITED TECHNOLOGIES
TWT GmbH Science & Innovation
Linköping University
Newcastle University
MODELIOSOFT
controlLab
THE UNIVERSITY of York
Verified
AGROINTELLI
CLEARSY SYSTEM ENGINEERING

Horizon 2020 Programme

Tutorial Schedule

- **Agricultural robotics, Agro Intelligence, Denmark**
- Building automation for HVAC systems, UTRC, Ireland
- Routing for electric vehicles, TWT, Germany
- A distributed railway interlocking system, Clearsy, France
- Use of INTO-CPS for large ship engines at MAN, Denmark
- Others:
  - Continental, Romania
  - European Space Agency, The Netherlands
  - Beumer, Denmark

The Robotti Case Study

Agrointelli and INTO-CPS

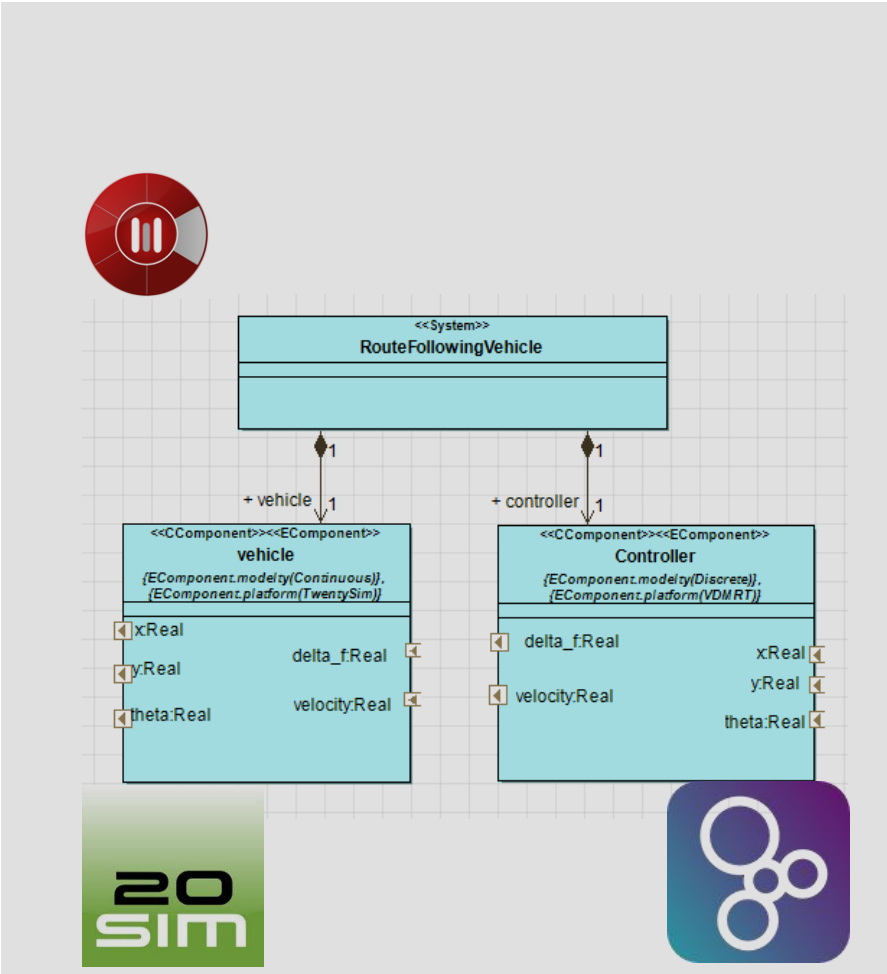
- Development of Robotti using the INTO-CPS tool chain
- Robot consistent of multiple interacting systems
    - Mechanical
    - Electrical
    - Control
    - Navigation
    - Etc.

Horizon 2020 Programme

The Robotti Case Study

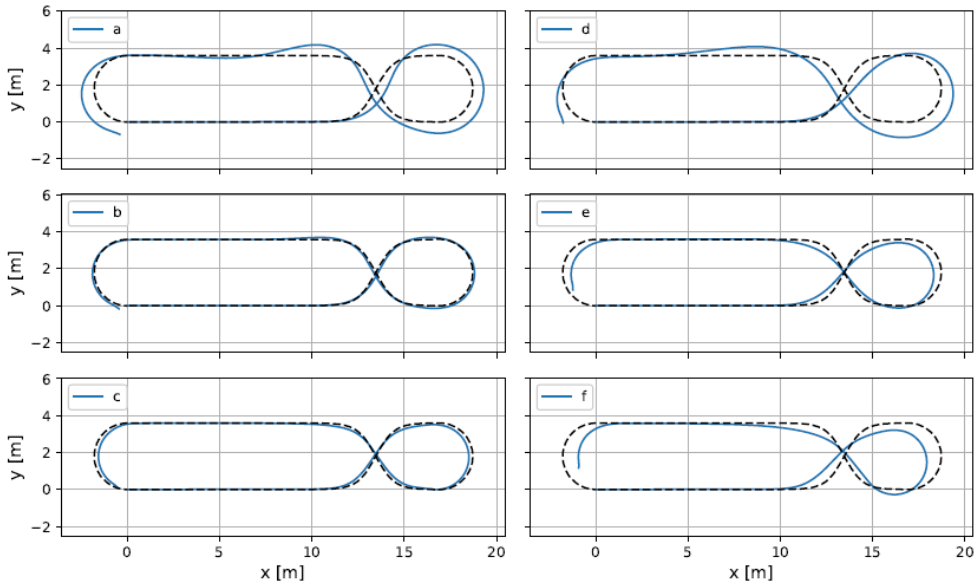
Results (selected)

- A model-based approach of engineering through INTO-CPS
- Investigating interacting dynamics
  - Mechanical system
  - Steering Controller



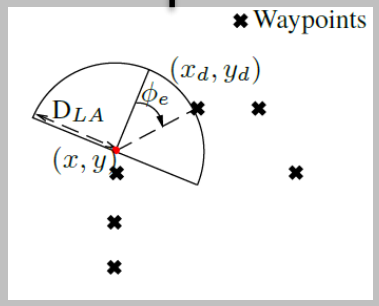
The Robotti Case Study

Results (selected)



Vehicle Dynamics FMU

INTO-CPS Application



Steering Controller Dynamics FMU

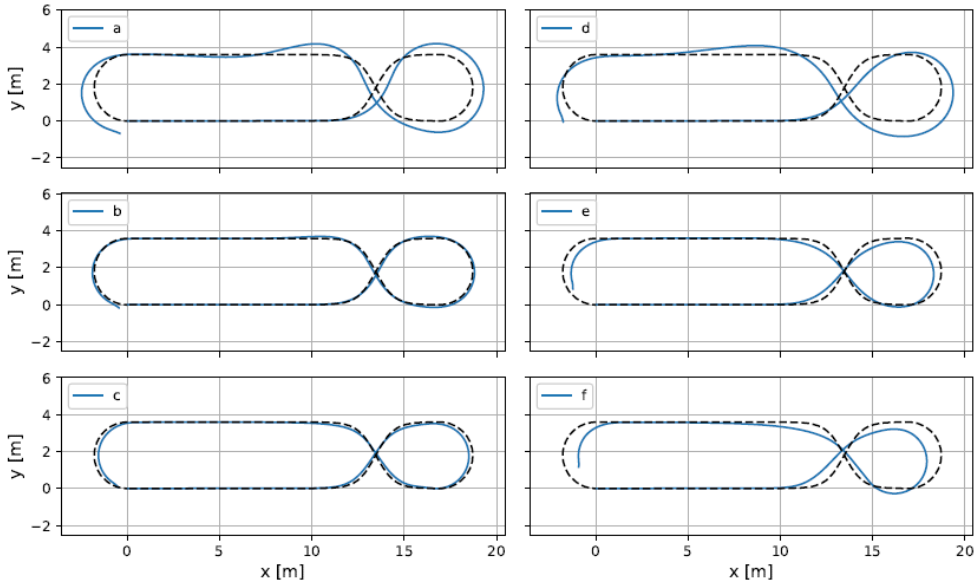
Exploring Design Space

Manual Investigation

Example: No. of combinations:

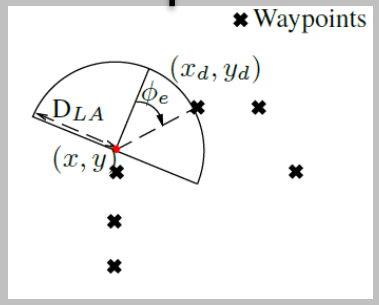
$$2 \cdot (3) \cdot 1 = 6$$

"… all right, we'll survive,
we can test this"



INTO-CPS

INTO-CPS Application



1 Chacteristic parameter
Undertaking
1 value

2 Chacteristic parameters
Undertaking
3 and 2 values

Now Automation is Needed

INTO-CPS

Manual Investigation

Example: No. of combinations:

$2 \cdot (3) \cdot 1 = 6$

"… all right, we'll survive, we can test this"

What if the design space is larger?

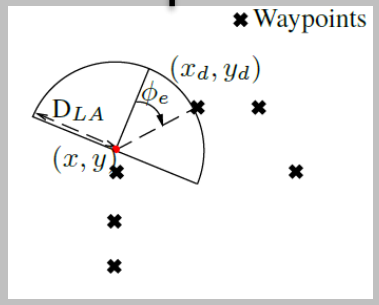
$5^3 \cdot 5^4$= 78.125 combinations

"… now we are in trouble"

3 Chacteristic parameters Undertaking 5 values

INTO-CPS

INTO-CPS Application



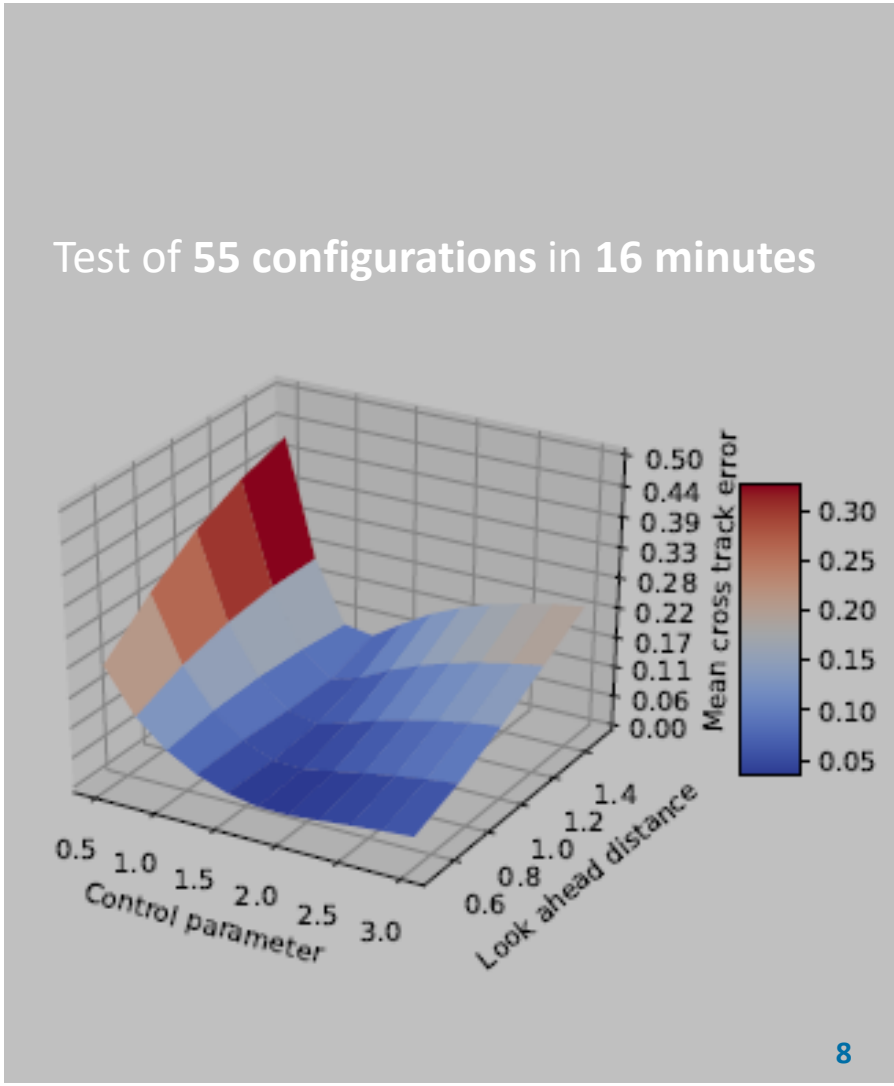
4 Chacteristic parameters Undertaking 5 values

Visualising Results is Valuable

INTO-CPS

Results (selected)

- A model-based approach of engineering through INTO-CPS
- Investigating interacting dynamics
  - Mechanical system
  - Steering Controller
  - DSE – experiment
    - Changing controller parameter
    - Changing look ahead distance
  - Test of 55 configurations in 16 minutes



Visualisation is Valuable

INTO-CPS

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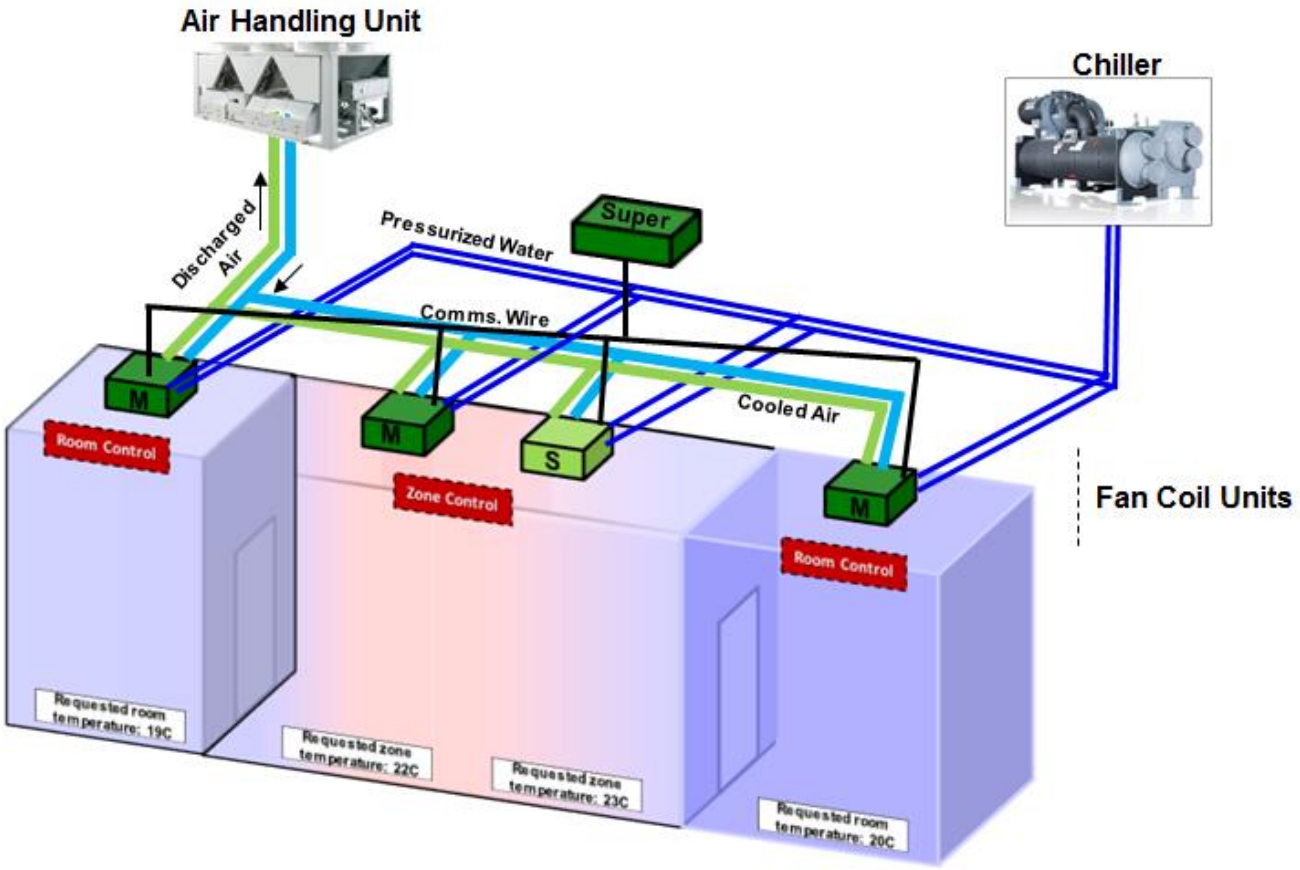
The HVAC Case Study

- Users set temperatures
- FCUs control temperature
- Chiller provides cool water
- AHU provides fresh air

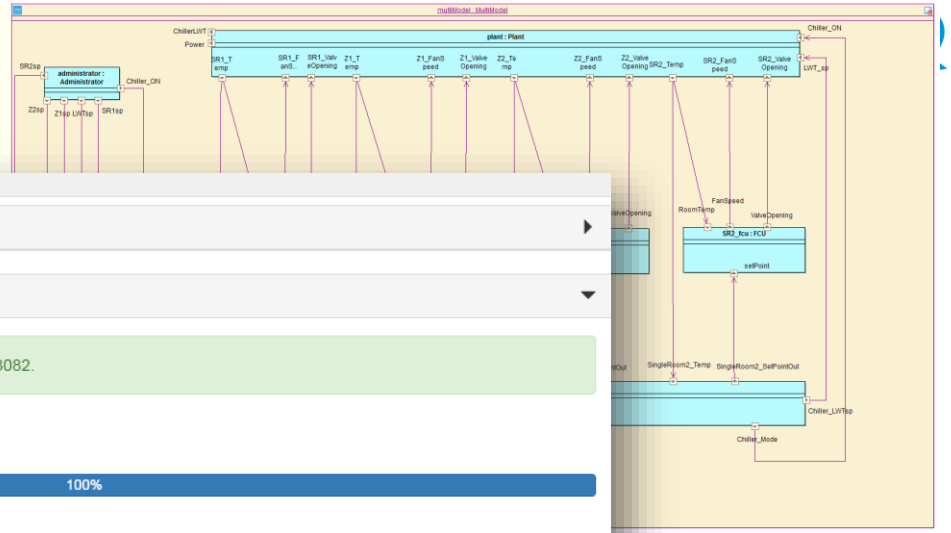


Additional Features Considered

- Communication between FCUs and Supervisor
- Fault Tolerance
- Equipment and Controller Performance
- Energy Consumption
- User Comfort

Building case

- FM



File Edit View Window Help

DSES

FMUS

- Dymola
  - Aquasmart_Controller_N
  - INTO_0CPS_Component_
  - INTO_0CPS_Component_
  - INTO_0CPS_Year3_Finall
  - INTO_0CPS_Year3_Finall
  - INTO_0CPS_Year3_Finall
  - INTO_0CPS_Year3_Finall
- Simulink
  - FaultySR1
  - FaultySR2
  - FaultyZ1
  - FaultyZ2
  - SR1
  - SR2
  - Z1
  - Z2
- VDM
  - BlackHole
  - VDM-Supervisor-2Master
  - VDM-Supervisor-MasterSl

MODEL-CHECKING

MODELS

MULTI-MODELS

+ NotWorking-Scenario2

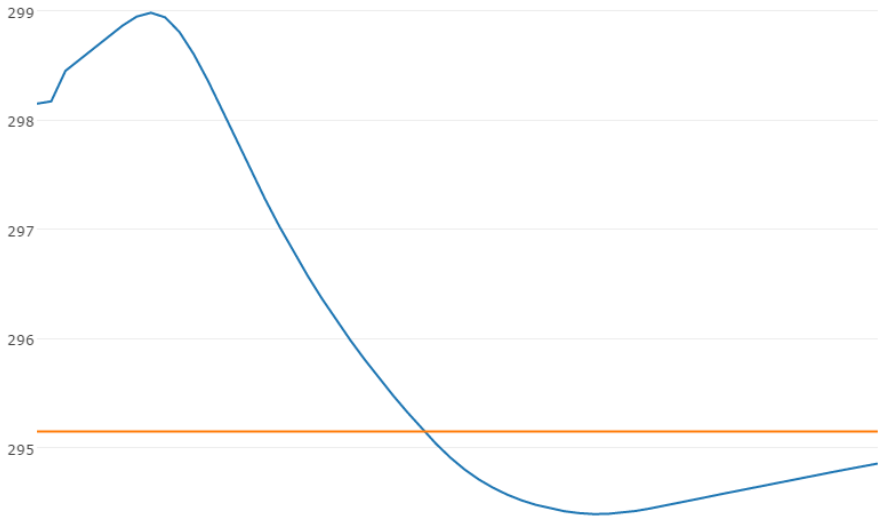
Configuration

Simulation

Co-Simulation Engine, version 0.2.6, online at localhost:8082.

▶Simulate

100%



blockset (R2011a+)
neration from the
gle script, from one or
cks

Air Handling Unit

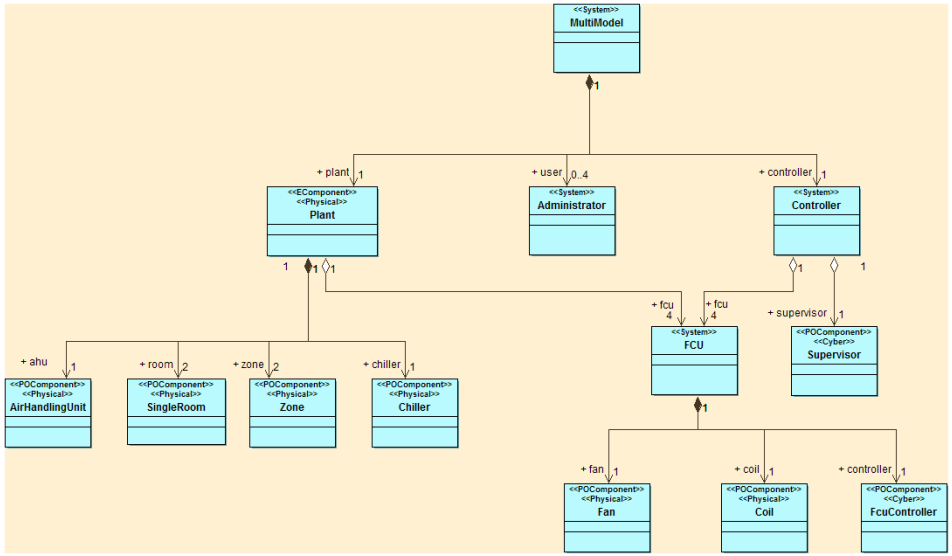
delled in Modelica
air to the FCUs

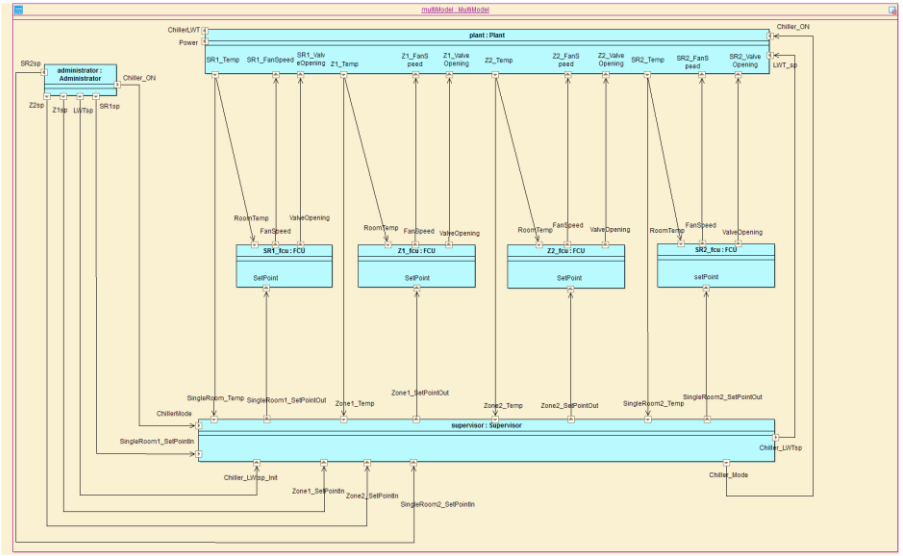
nows
uations

- Montluel test site: 71 FUCs, 1052 m², 121 occupants

Architectural models in SysML

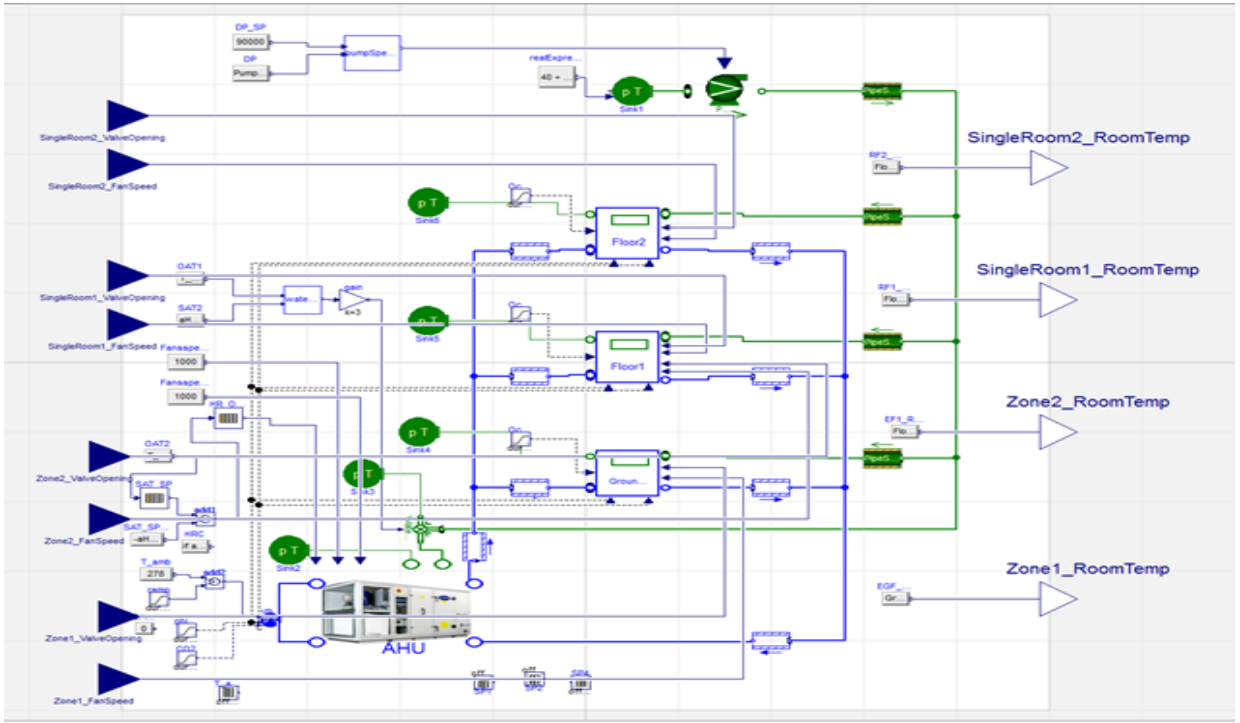
- System decomposition and architecture
- Connections between FMUs for Co-Simulation
- Value: common representation of the system for all technical team members





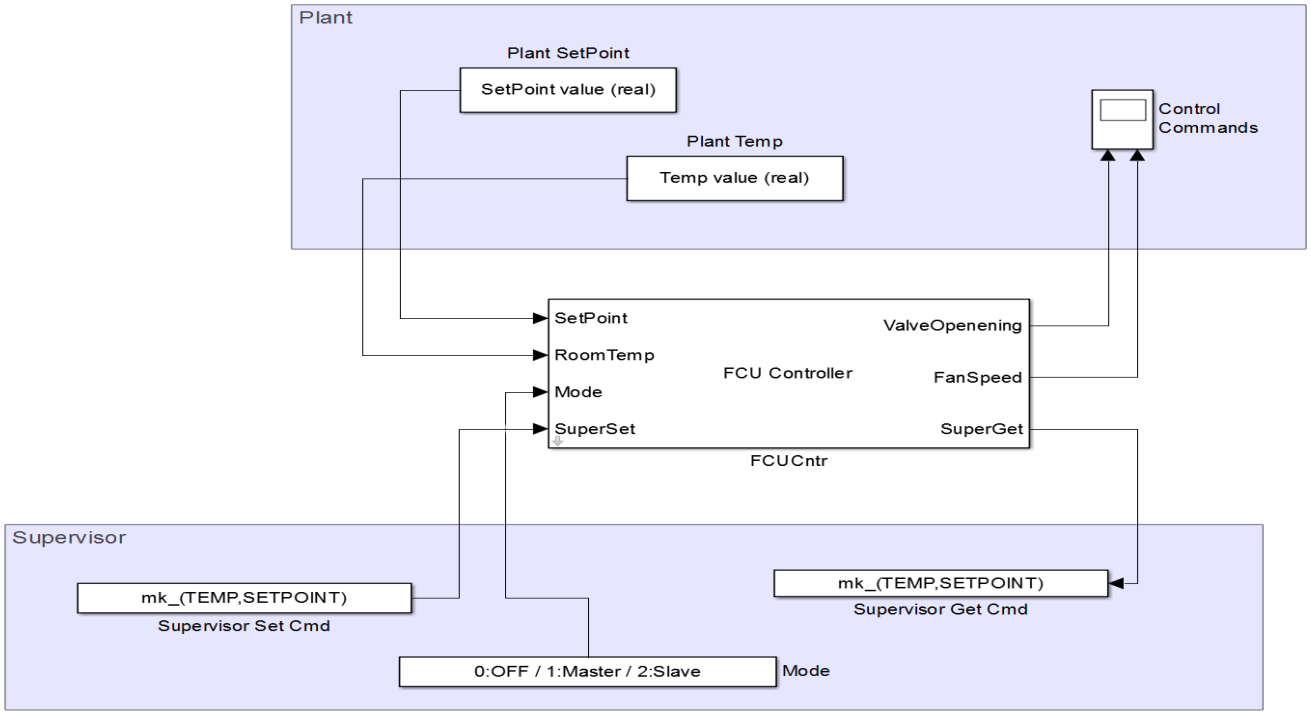
Plant models in Dymola

- Describe the physical aspects of the system: air flow, temperature exchange, etc.
- Components: rooms, fan coil units, **chiller**, etc.
- Value: viability of UTC HVAC modelling libraries for FMI



Control models in Simulink

- PI controllers for the Fan Coil Units
- Newly introduced – improved performance over Y2
- Communication with supervisor model over the FMI
- Value: understanding of possibilities of Co-Simulation for Simulink



Discrete Event models in VDM

- Supervisory control models
- Fault detection and tolerance
- Coordinates set points of FCUs
- Simple communication with FCU controllers over FMI
- Heavily refactored from Y2
- Value: injecting new tools and formalisms in UTC tool chain

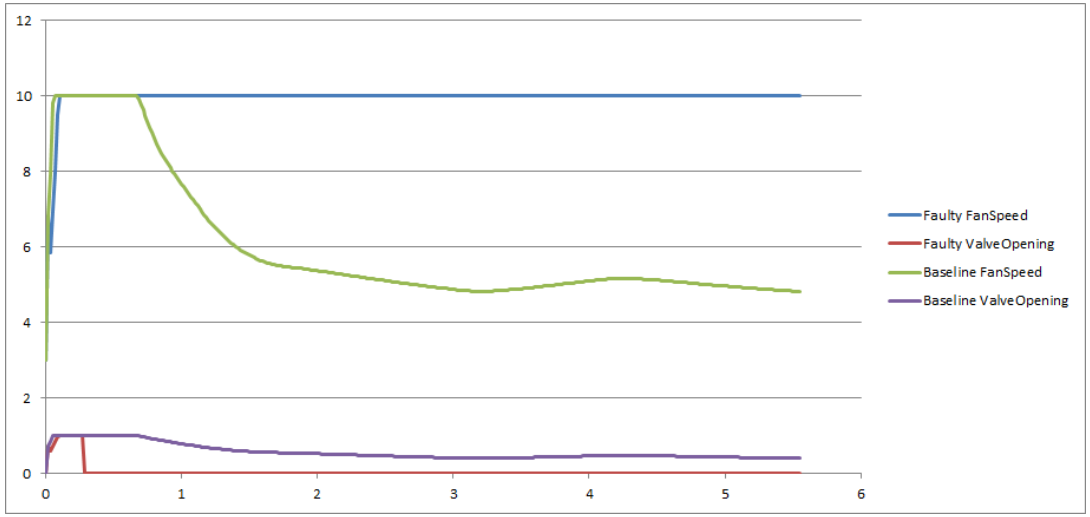
```
private setPointAdjust: Controller ==> ()
setPointAdjust (fcu) == (
  let sp = fcu.getSPValue()
  in (
    if minTemp >= 0 and sp < minTemp then (
        fcu.setSuperSetPoint(minTemp);
    );
    if maxTemp >= 0 and sp > maxTemp then (
        fcu.setSuperSetPoint(maxTemp);
    );
  );
)
post maxTemp > 0 and minTemp >0 ->
      fcu.getSPValue() <= maxTemp and
       fcu.getSPValue() >= minTemp;
```

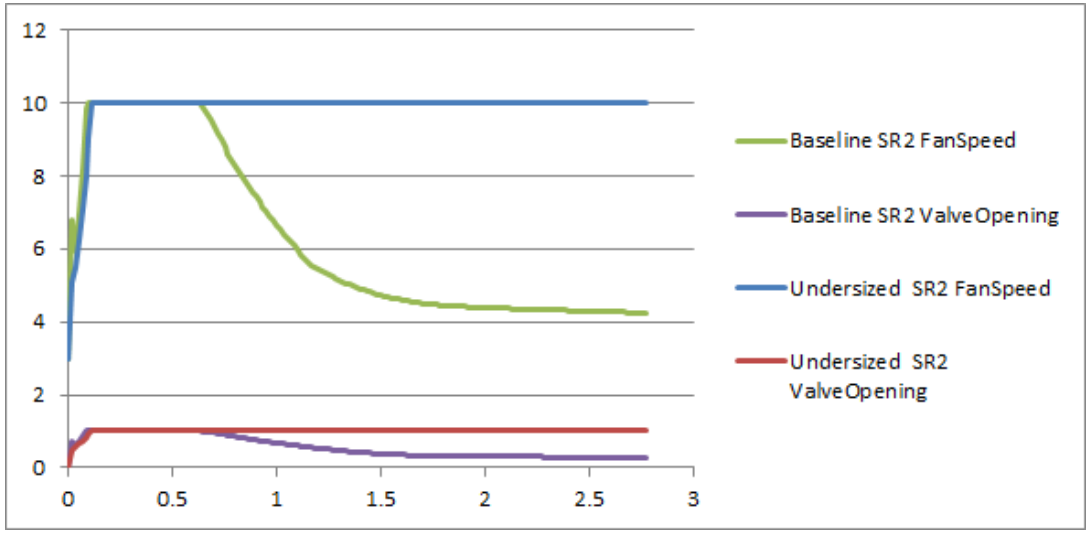
```
public setSuperSetPoint : real ==> ();

public promoteToMaster : set of Controller ==> ();

public demoteToSlave : () ==> ();

public turnOff : () ==> ();

public getRole : () ==> Role

public getSlaves : () ==> set of Controller

public getSPValue : () ==> real
```

Co-simulation Experiments

INTO-CPS

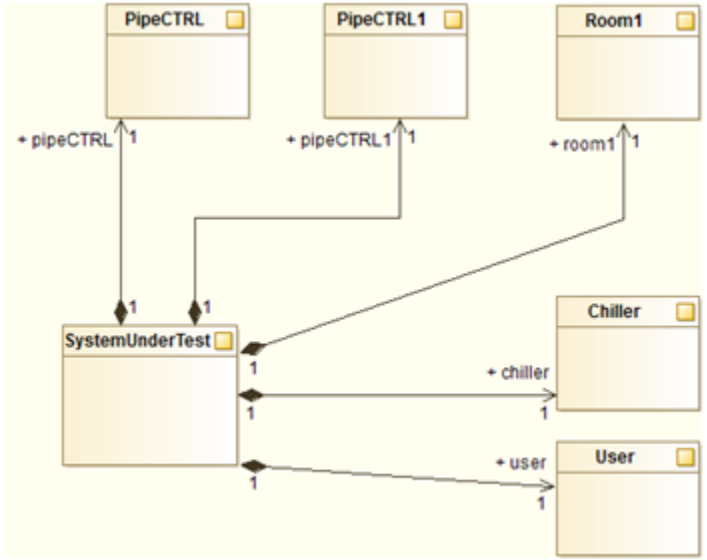
- Combine 10 FMU variations
- 6 HVAC Scenarios
- Full day experiments
- Evaluate performance and robustness of system
- Energy consumption
- User discomfort
- Fault tolerance
- Sizing

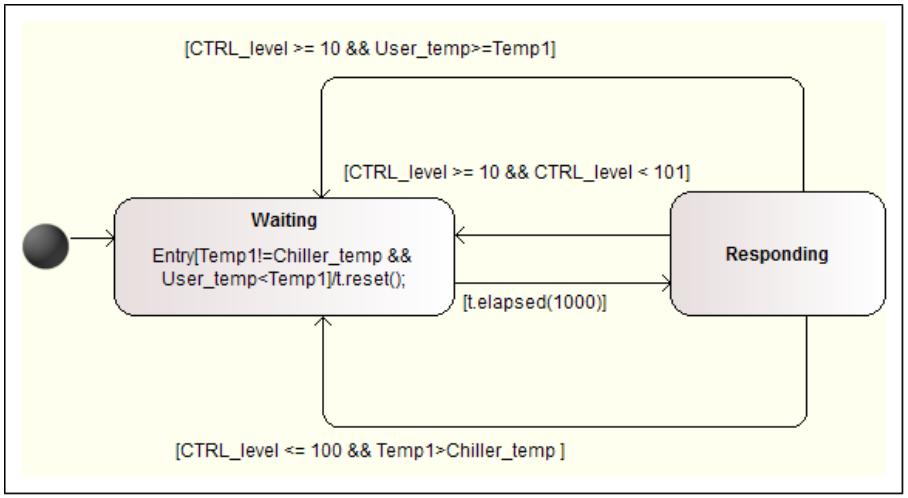




Test Automation Experiments

- Abstract representation of complex components
  - Ex: chiller
- Efficient property verification
- Reuse in full co-simulation
- Test Automation Results:
  - App Test Goals Coverage: 7/8
  - RTT BCS Coverage: 16/18
  - RTT Full Coverage: 83/193
  - Property Verification: 1/1





UTRC Lessons Learned

- Established FMI-based tools and flows for CPS design
- Disseminate through broader UTC community
- Lessons learned:
  - FMI Maturity provides new dimensions of model quality
  - Cross-disciplinary collaboration: challenging but rewarding
- Value:
  - Scalability of co-simulation
  - 3D Co-Simulation

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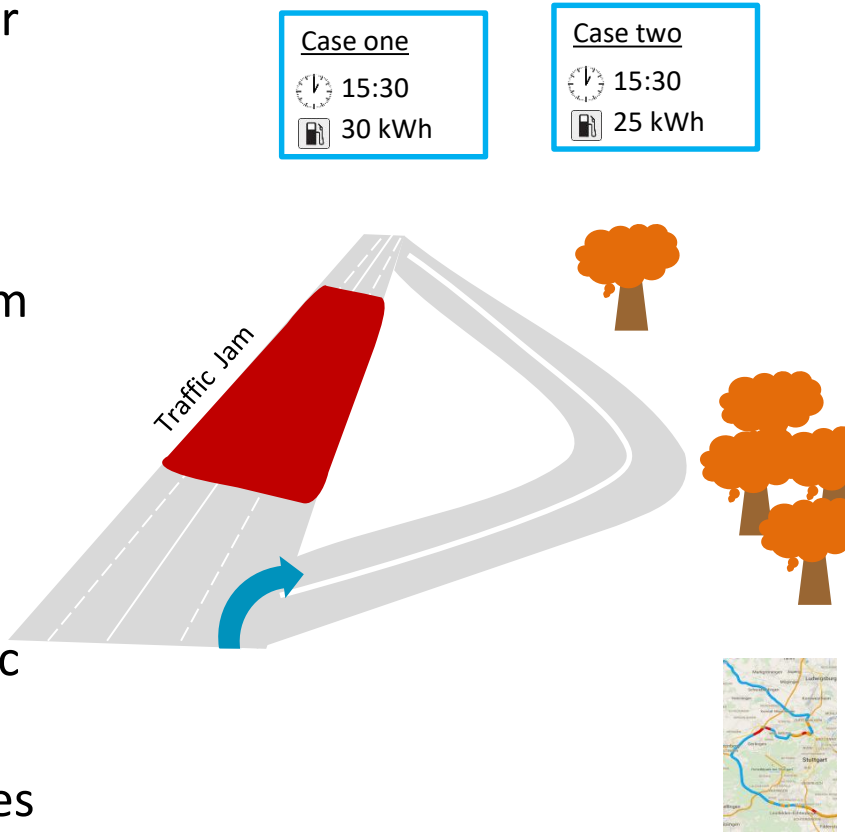
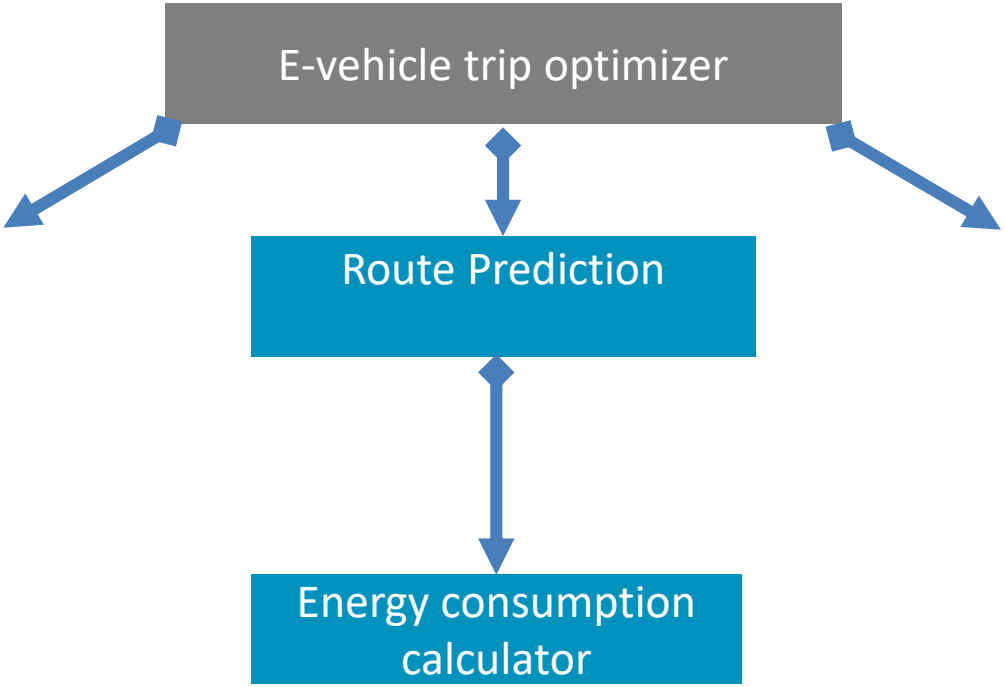
trip & range optimization assistant for electric vehicles

- Route planning is based on statistical data for velocity/traffic
- Navigation systems optimize for fastest or shortest route, not for most efficient.
- Navigation systems do not tackle the problem of limited range/recharging capabilities of electric vehicles



- **Goals**
- Realistic prediction of the range of an electric car
- Continuously monitor the journey for changes in traffic/weather
- Influence driving style to optimize efficiency

Components of the Trip Advisor



Energy Consumption Calculator

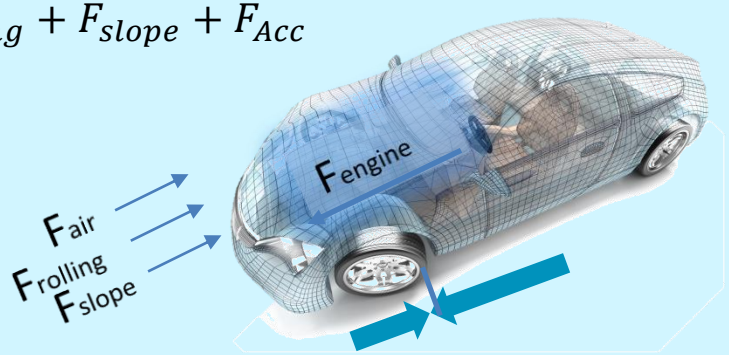
INTO-CPS

covered distance:Real
current velocity:velocity
road slope:%
suggested velocity:velocity

temperature:Temperature
solar radiation:surface power density
humidity:%
atmospheric pressure:pressure

Longitudinal Dynamics/Energy Calculation

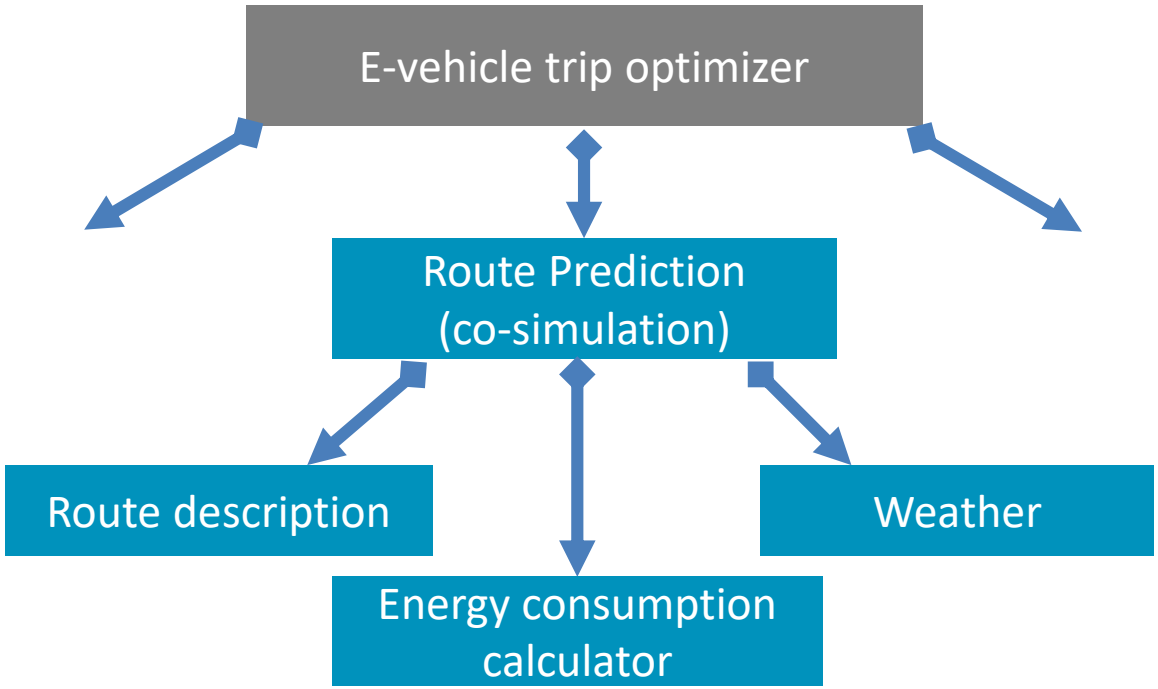
$$F_{engine} = F_{air} + F_{rolling} + F_{slope} + F_{Acc}$$



wheels
gear
engine
recuperation
aux. systems (A/C)
battery

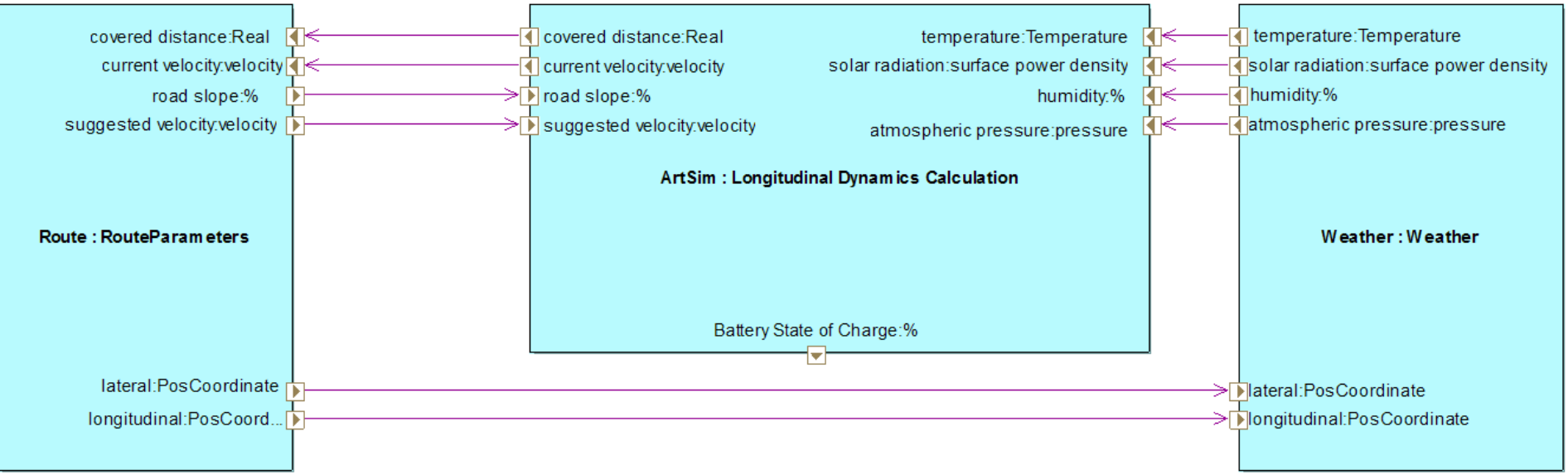
Battery State of Charge:%

Components of the Trip Advisor

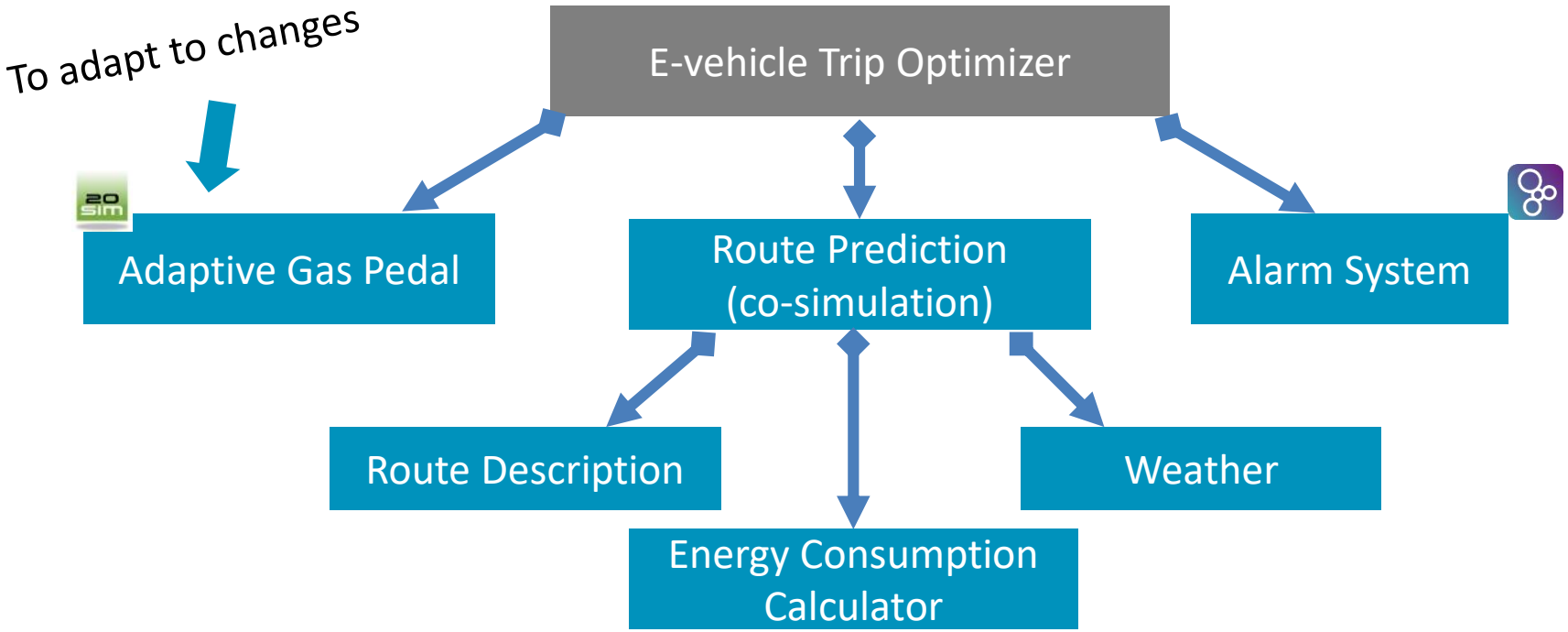


Route and Weather Data

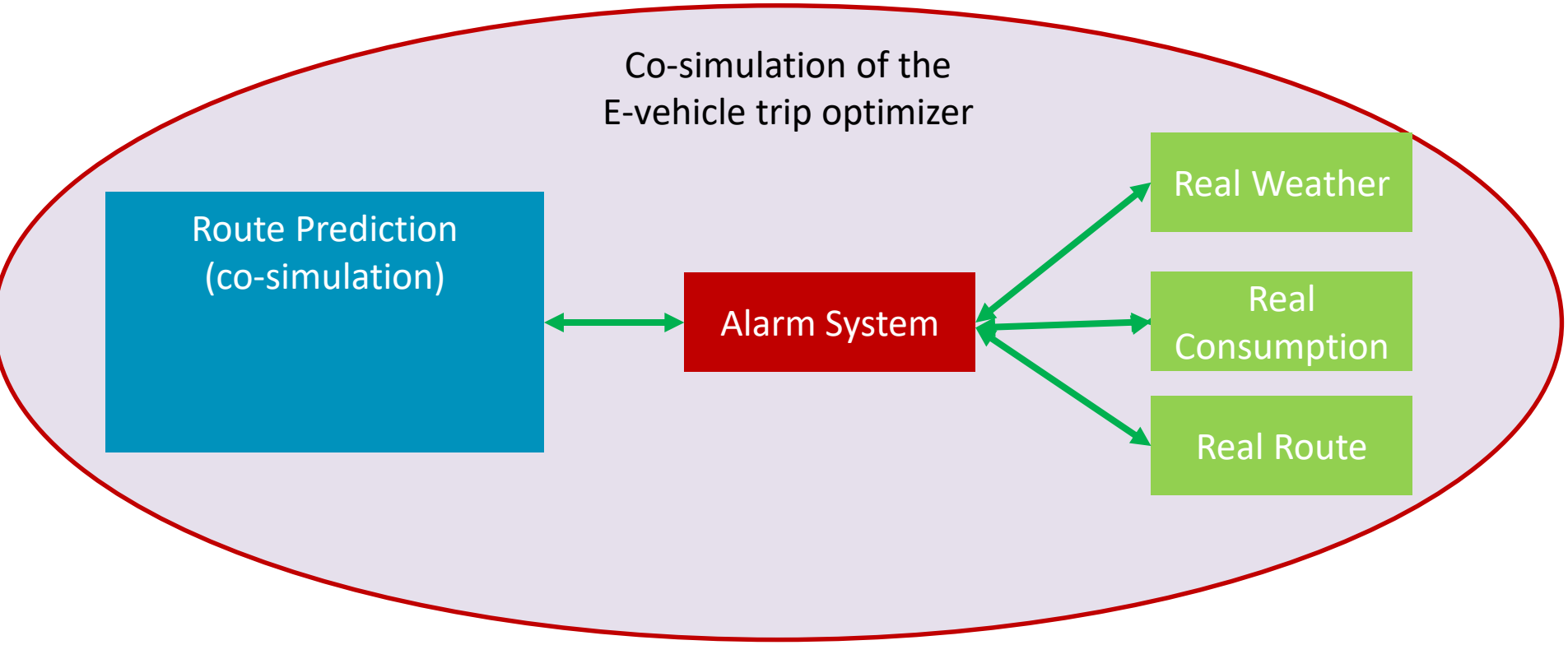
- Data is requested from GoogleMaps/OpenWeatherMaps web services via http-APIs
- Received JSON data are processed and provided as signals in a co-simulation



Components of the Trip Advisor



Testing the trip optimizer Alarm System



- Test the alarm system by simulating the trip execution under various conditions
- Redo the Route Prediction if a deviation is detected by the Alarm System
- Start a co-simulation from a co-simulation?

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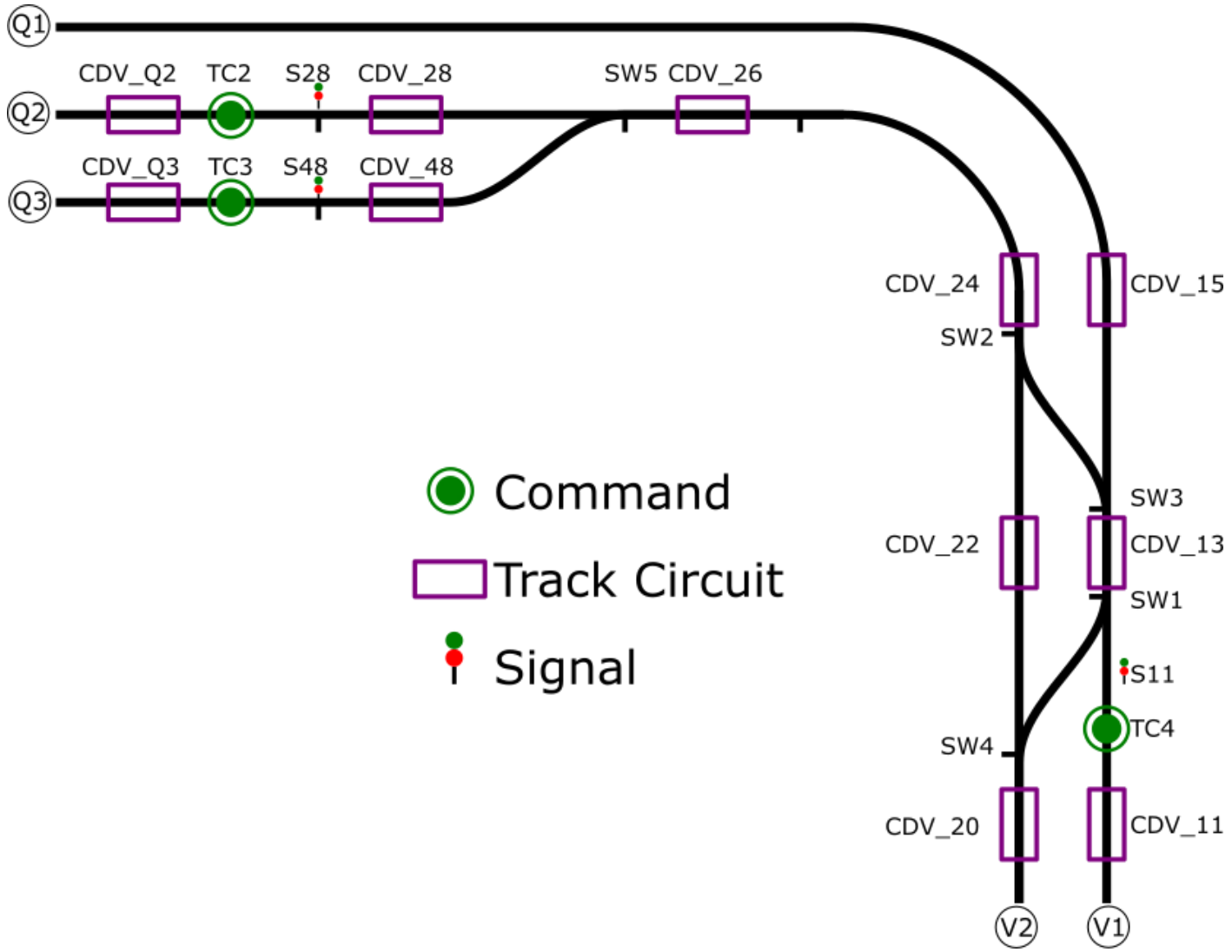
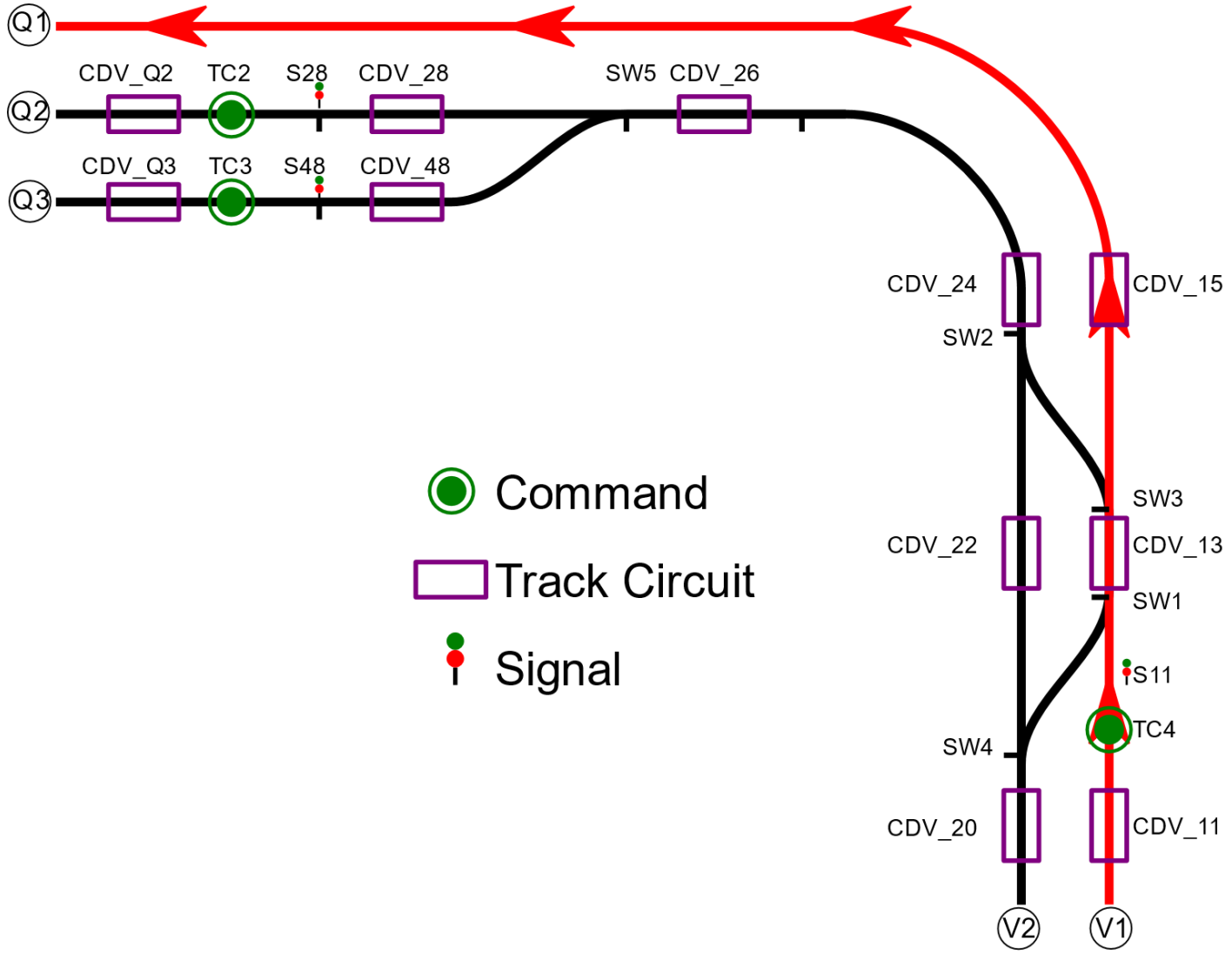
The Interlocking System

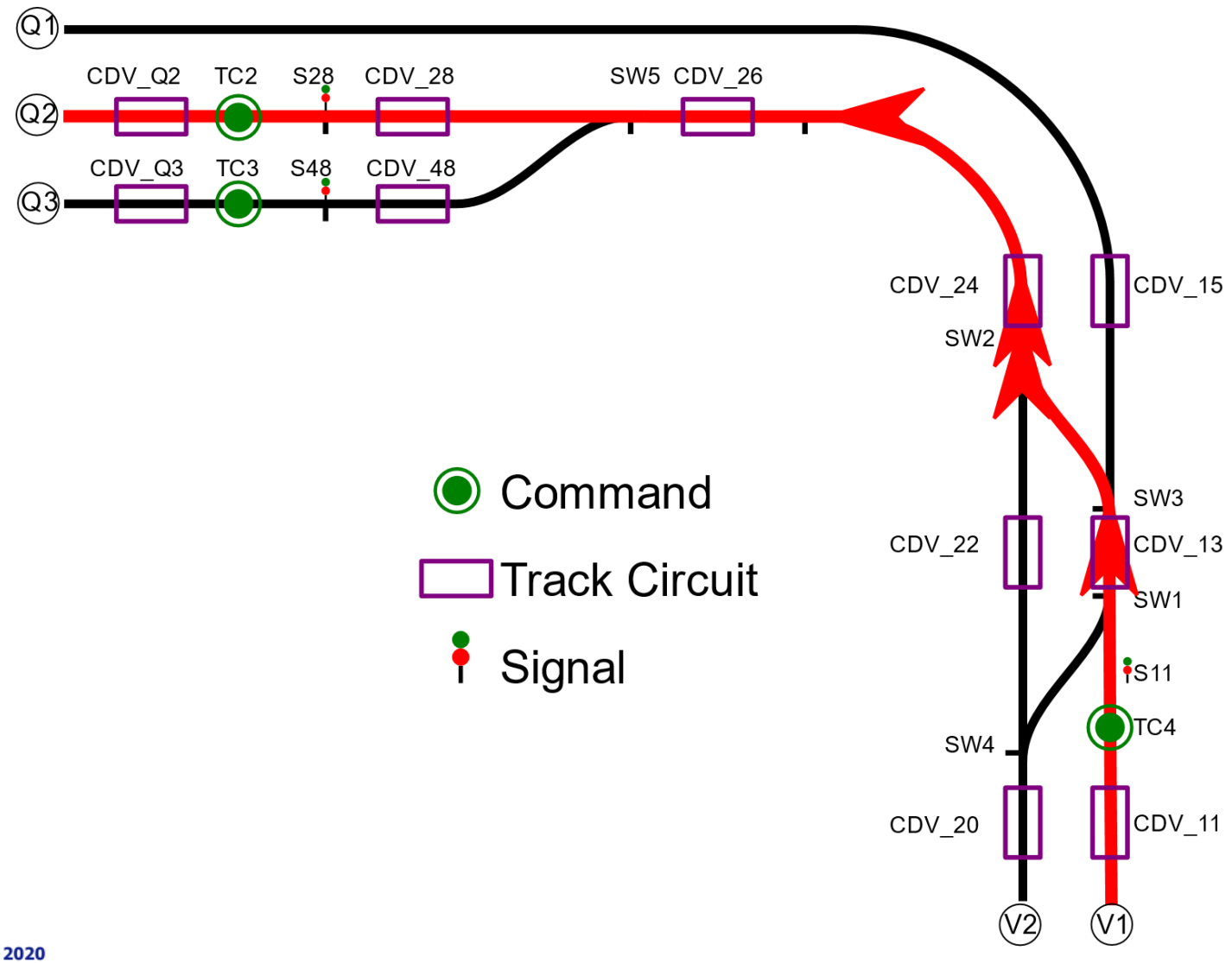
The Interlocking System



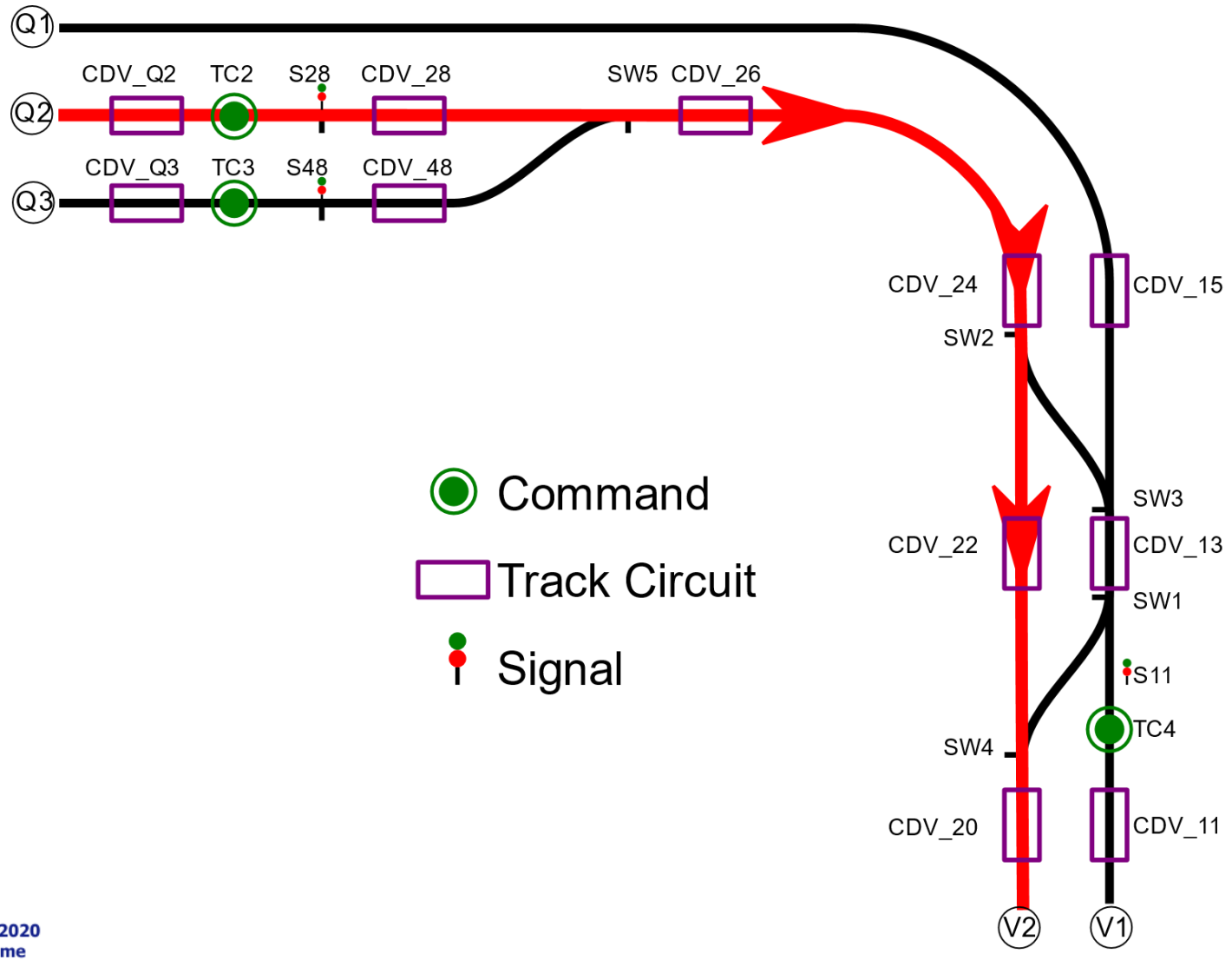
5 Possible Routes: #1



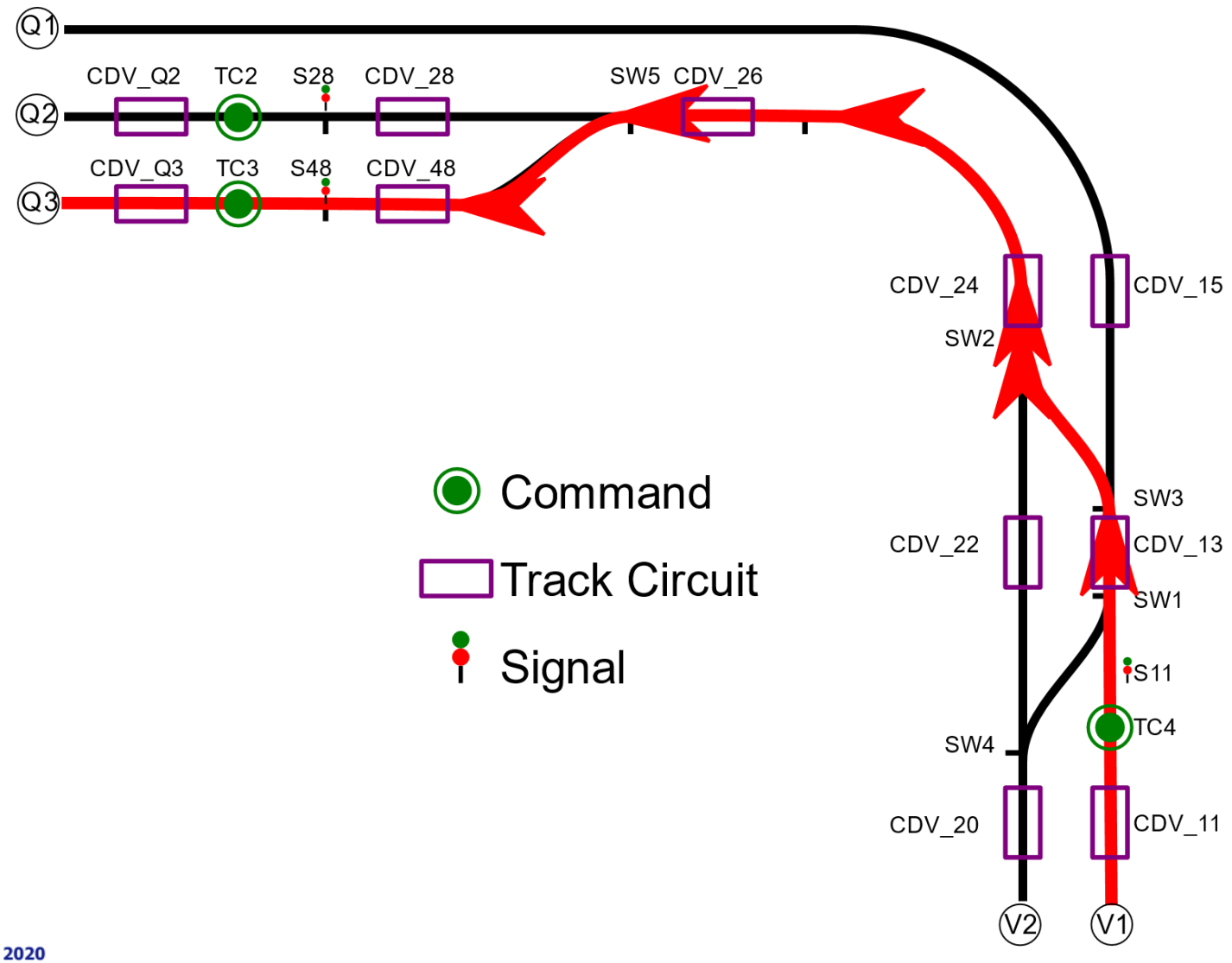
5 Possible Routes: #2



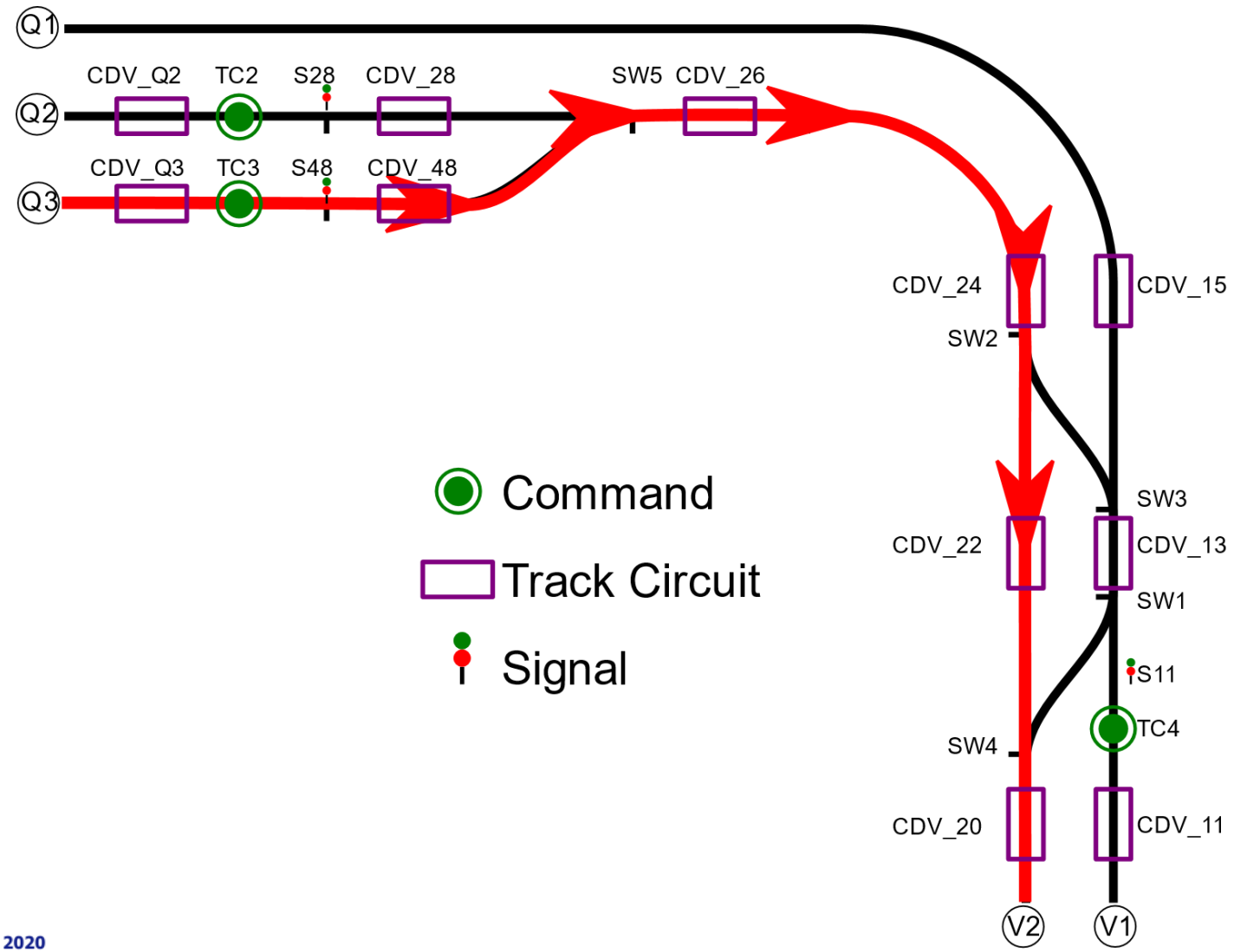
5 Possible Routes: #3



5 Possible Routes: #4



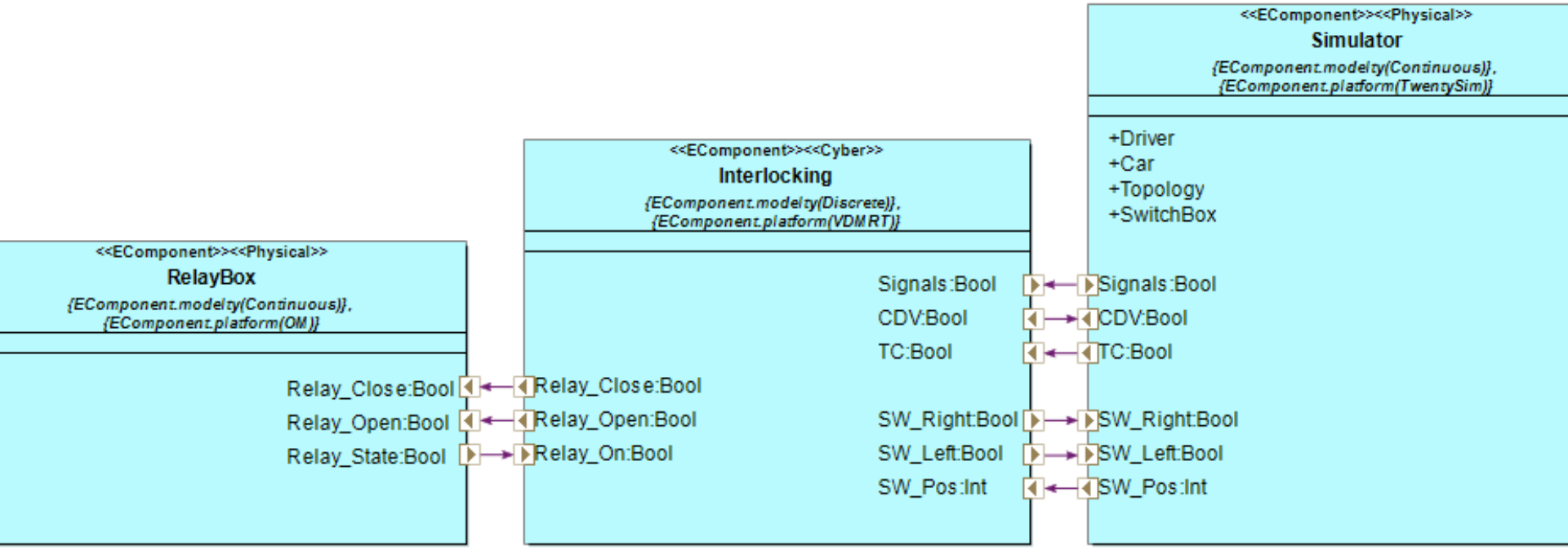
5 Possible Routes: #5



System Modelling

INTO-CPS

Modelio



Model description

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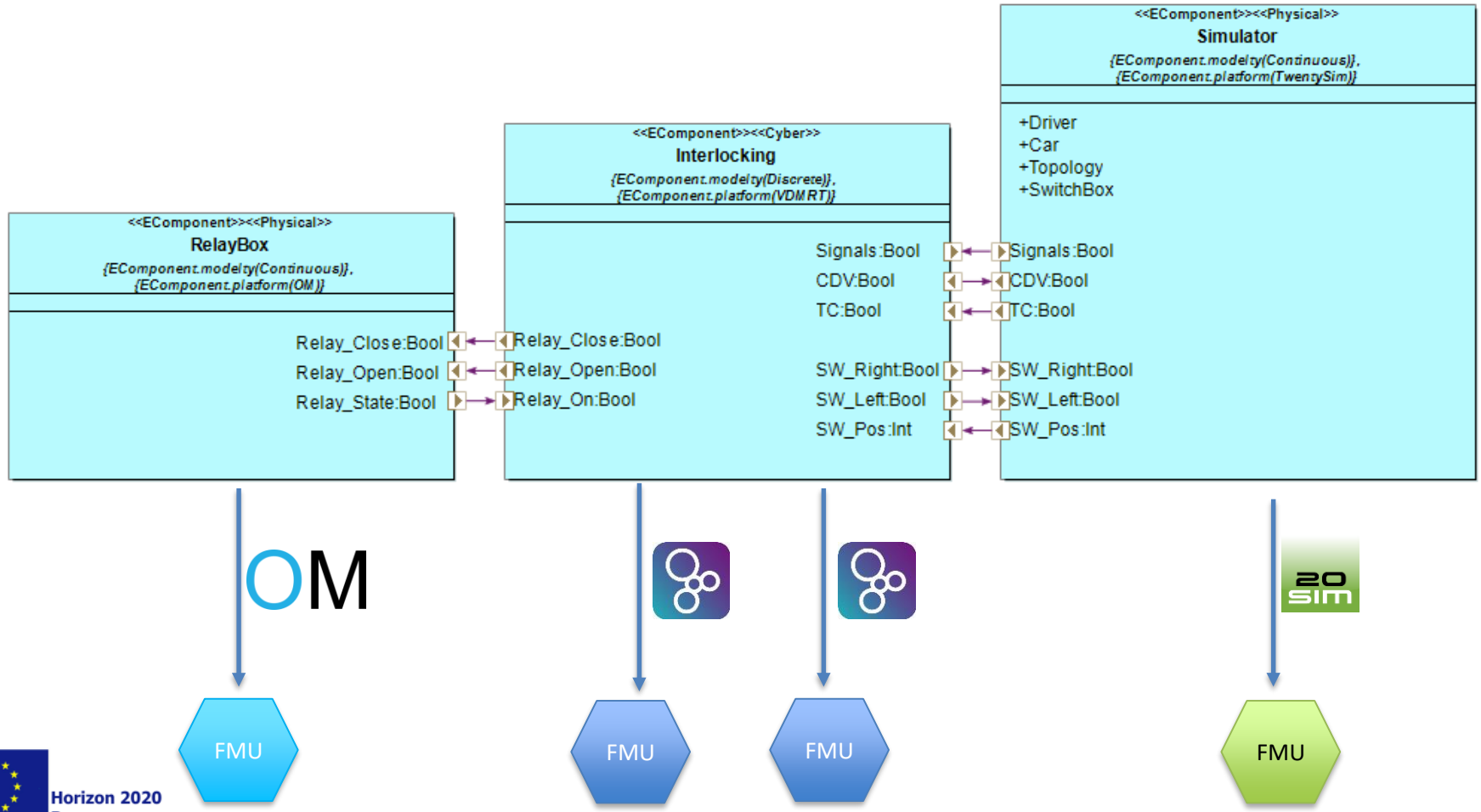
Model description

Model description

20 sim

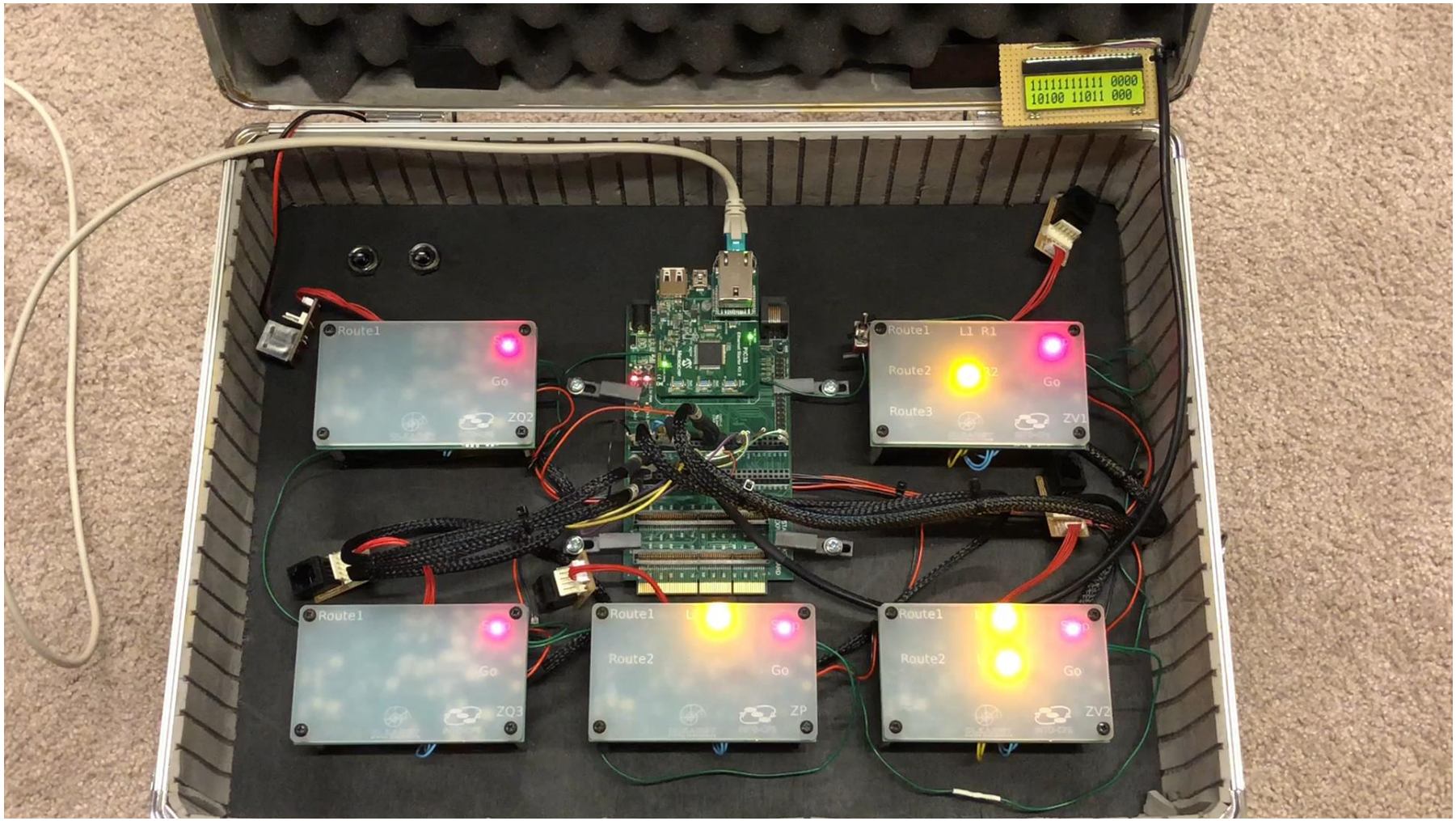
Programme

Generating FMUs

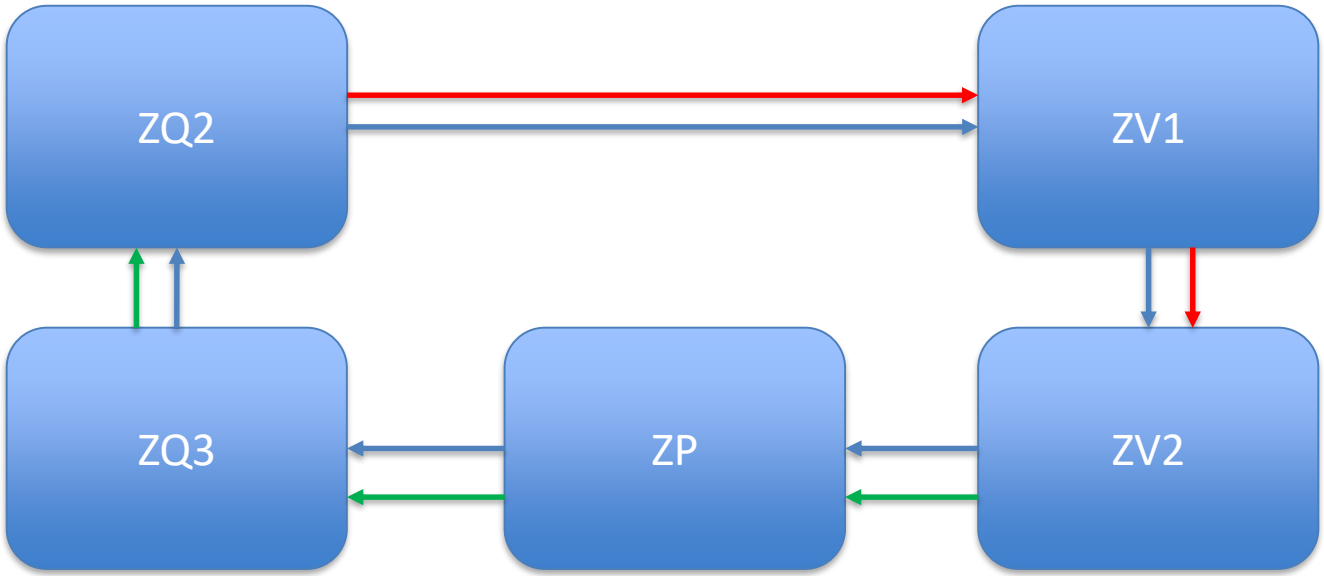


Code Generation and Prototype

INTO-CPS



Code Generation and Prototype



Modules
Network
Function Call
Value Return

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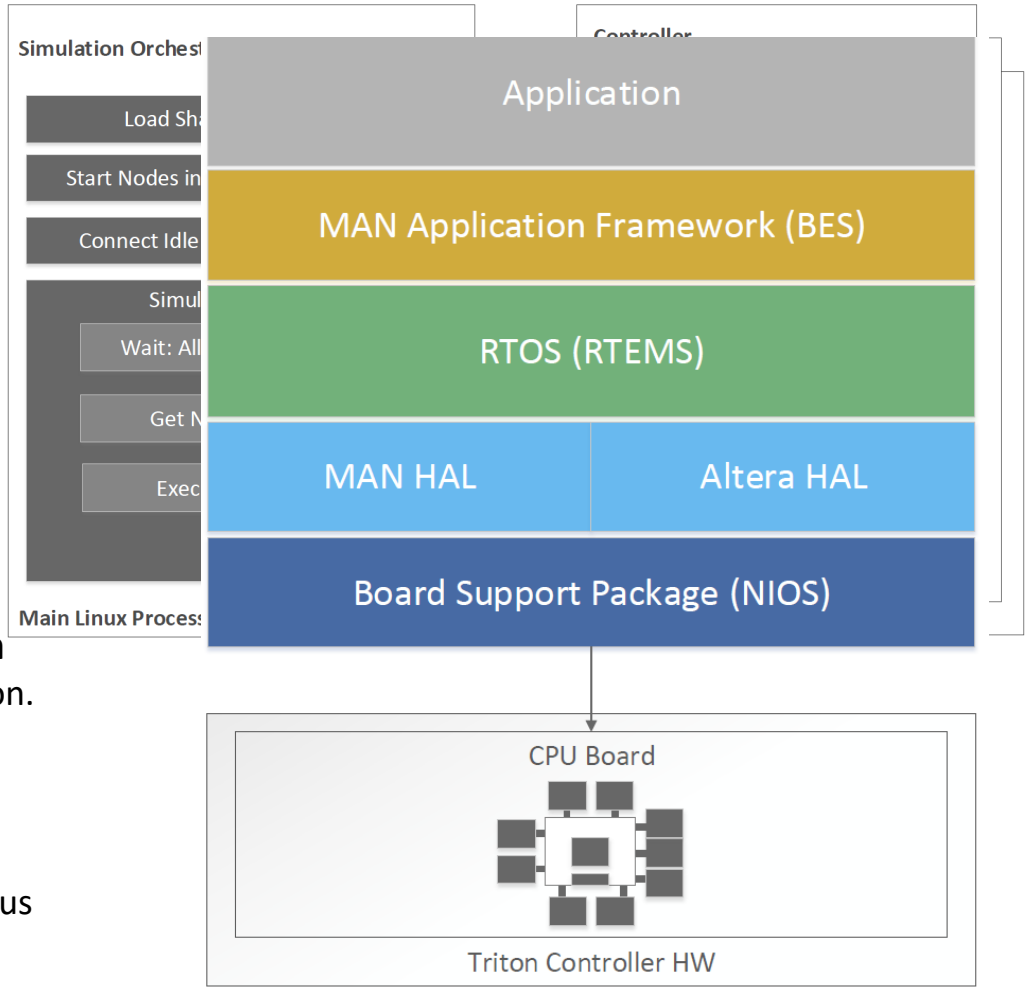
MAN produce engines for large ships

Embedded Control Software Simulation

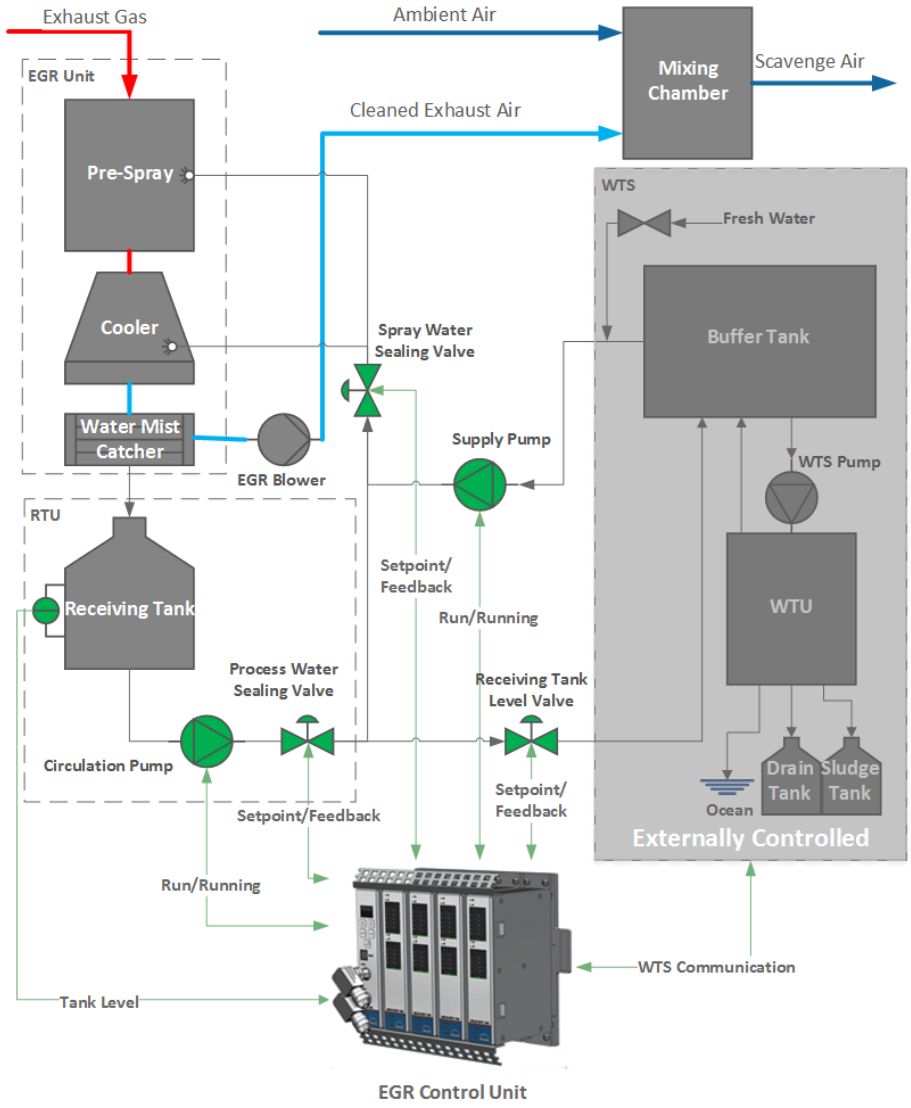
Simulation of CPS

- **Software Application Environment**
  - C++ Environment
  - Component Based Architecture
  - Dynamic Simulation Environment (DSE)
    - ODE Solver
    - Higher Resolution Kernel
    - Model Library
- **Cross Compiler**
  - Build for Target (Embedded Core)
  - Build for Simulation (x86)
- **Controlling the Clock for Temporal Execution**
  - BSP-Idle thread used as hook to schedule execution. (Clock ticks, Interrupts, Communication)
- **Manager Orchestrating Simulation**
  - Multiple Controllers (Multi-threaded)
  - Implements FMI for orchestration of heterogeneous models and tools.



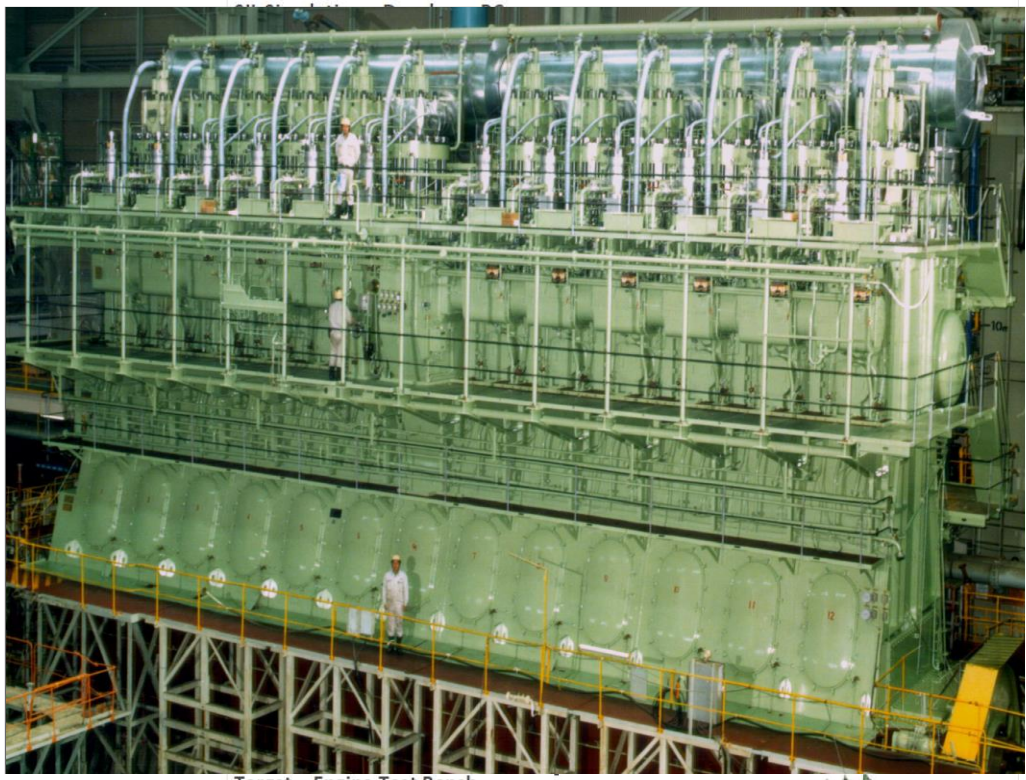
Simulation of Process Plant and Control

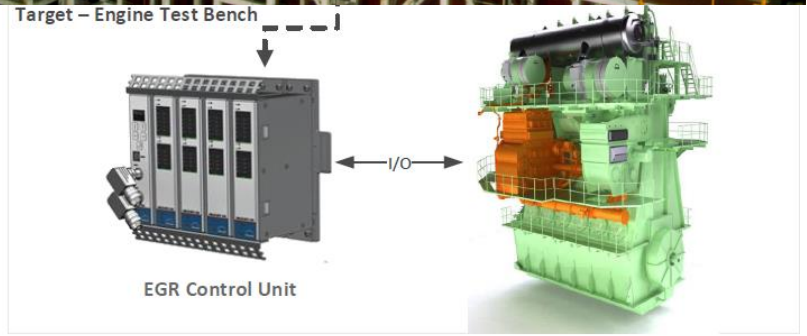
- **Exhaust Gas Recirculation Water Handling System (WHS)**
  - EGR exchange in-cylinder O_2 with CO_2 decrease in combustion speed lower peak temperatures during combustion lower thermal NO_x
  - Water Treatment System (WTS) Delivered by Alfa Laval
  - WHS Control
    - Main objective: To regulate Level in Receiving tank
    - EGR Control Unit
      - State Machine for Start Stop and Operation
      - PI-Controller for Receiving Tank Level



Simulation and Verification Process

- **SIL Verification**
  - Engine Simulation Unit (ESU)
    - DSE physical dynamics model of WHS
  - EGR Control Unit (EGRCU)
    - Complete EGRCU control software
- **HIL Verification**
  - Real embedded controllers
  - Engine Model in ESU
- **Test Bed Verification**
  - Real embedded controllers & engine
- **Results**
  - Working PI-controller
  - Water level overflow in Receiving Tank





Optimization of Development Process

Co-Simulation

- **Evaluation of Simulation Results**
  - Unhandled accumulation of water in Water Mist Catcher
  - Incorrect state machine handling of operation Shutdown
  - *Preliminary study in MATLAB had been simplified when moving to DSE (C++)*
  - *Test and Verification Cost approx.: XXX €*

- **Platform & Architecture Challenge**
  - Control System 32-bit Linux
  - 90% Organization tools 64-Bit Windows

- Solution: Distributed Co-Simulation

- **Targeting Co-Simulation**

1. Simulation of Control System In MATLAB
   - Redundancy in control model development
   - Physical Models still need to be converted to C++ for HIL testing

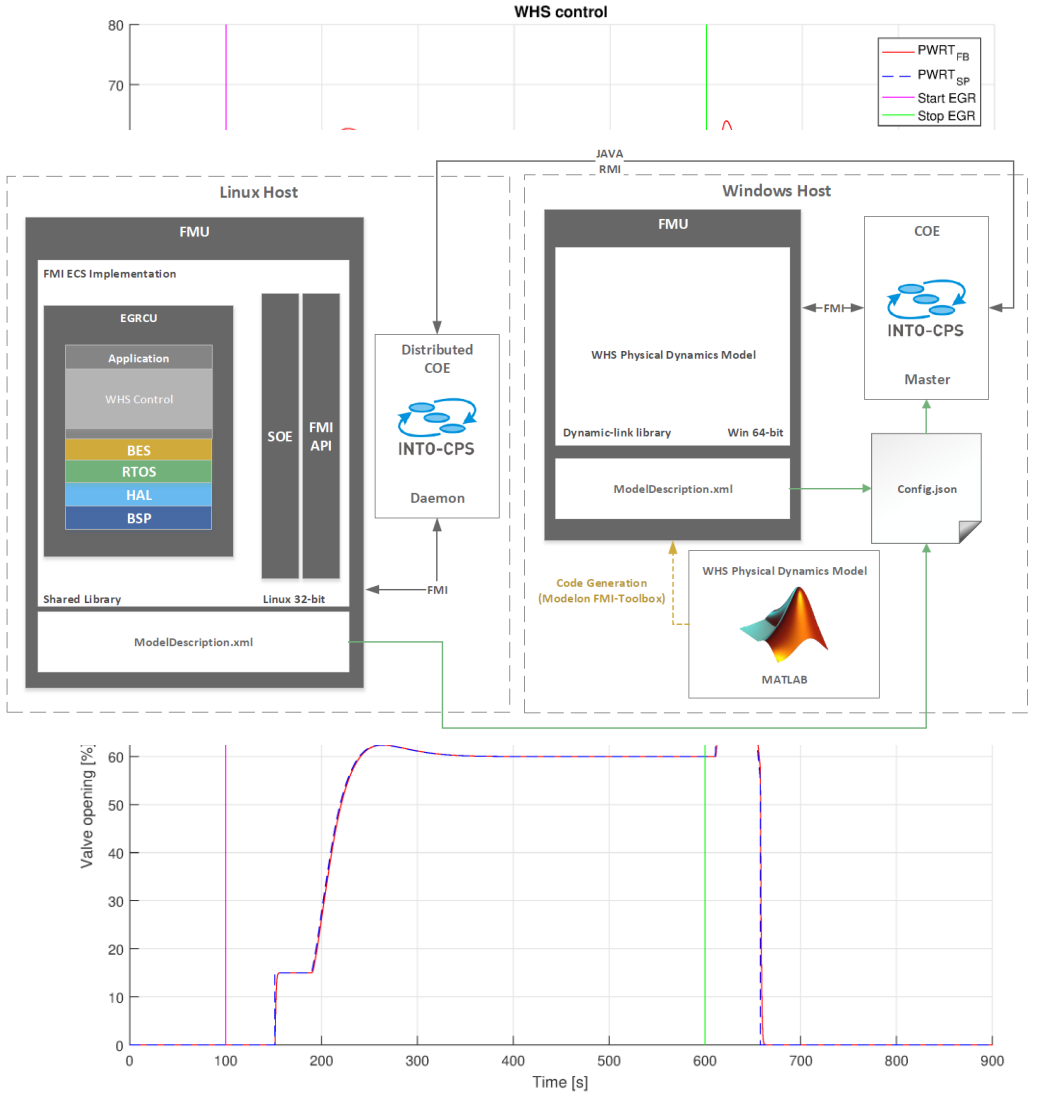
2. Enhancement of DSE Model.
   - Traditional Approach

3. Co-Simulation of Control System and MATLAB

Distributed Co-Simulation

Process Plant and Control System Verification

- **Linux Host**
  - Distributed COE Daemon
  - Control System FMU
    - Shared Library with FMI API
    - EGR Control Unit with WHS Control
- **Windows Host**
  - Master COE
  - Code Generated MATLAB FMU
    - WHS Physical Model
- **Results**
  - Higher fidelity model made it possible to develop a working state machine
  - Stable Water level in Receiving Tank

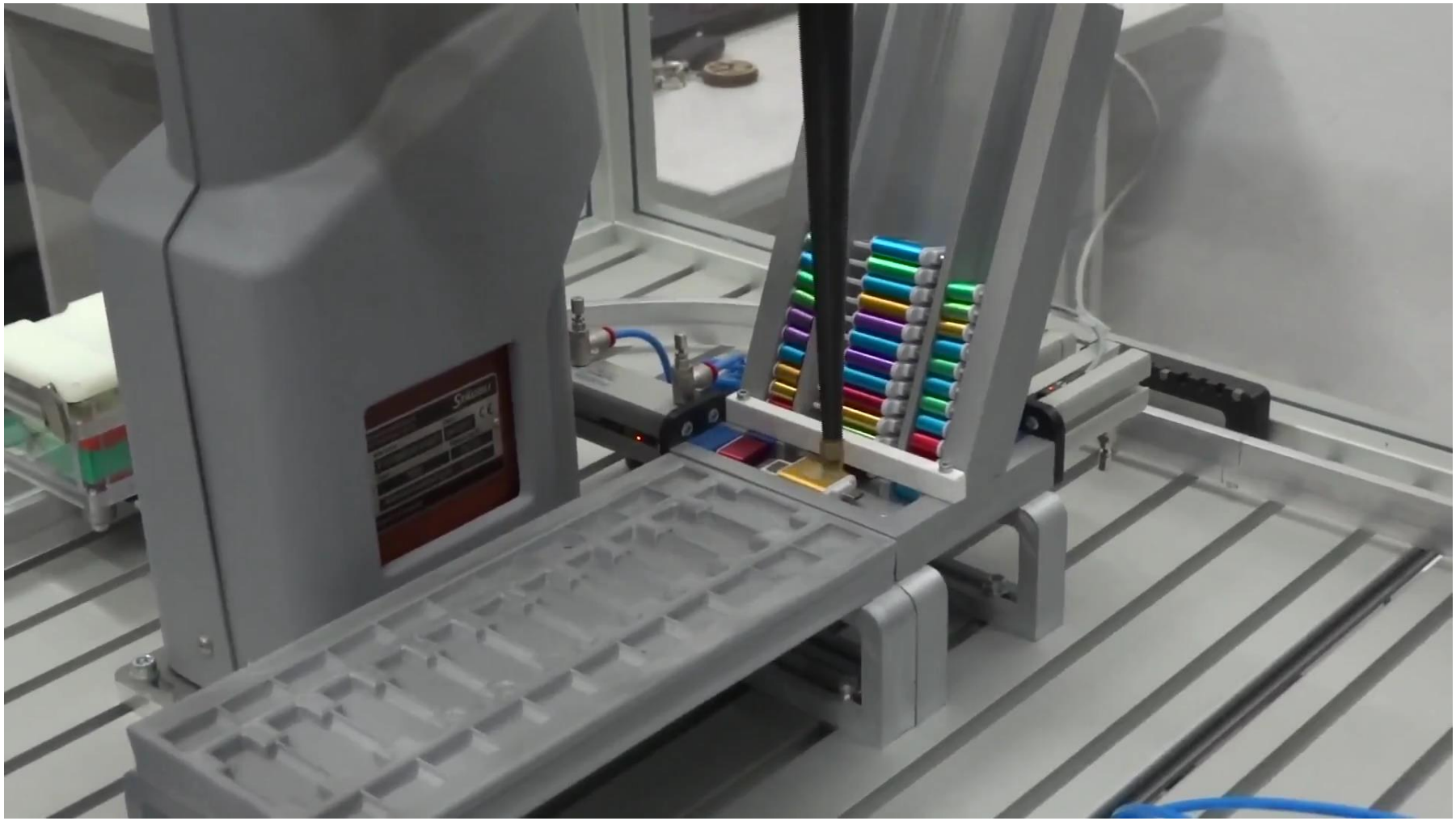


Tutorial Schedule

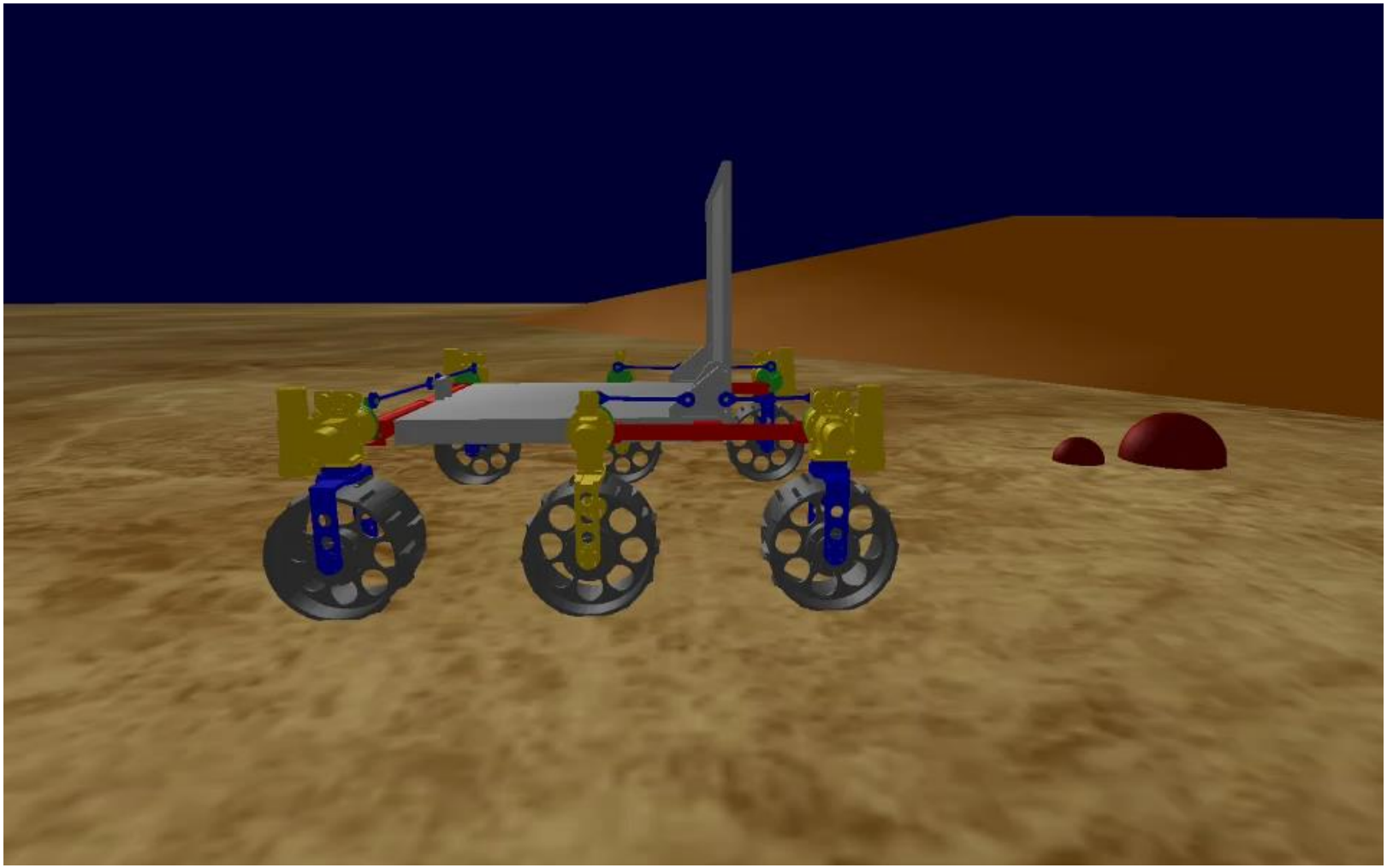
- ✓ Agricultural robotics, Agro Intelligence, Denmark
- ✓ Building automation for HVAC systems, UTRC, Ireland
- ✓ Routing for electric vehicles, TWT, Germany
- ✓ A distributed railway interlocking system, Clearsy, France
- ✓ Use of INTO-CPS for large ship engines at MAN, Denmark
- **Others:**
  - **Continental, Romania**
  - **European Space Agency, The Netherlands**
  - **Beumer, Denmark**

Continental, Romania

INTO-CPS



European Space Agency, Netherlands



Beumer, Denmark