10 Years of FMI
Where are we now?
Where do we go?

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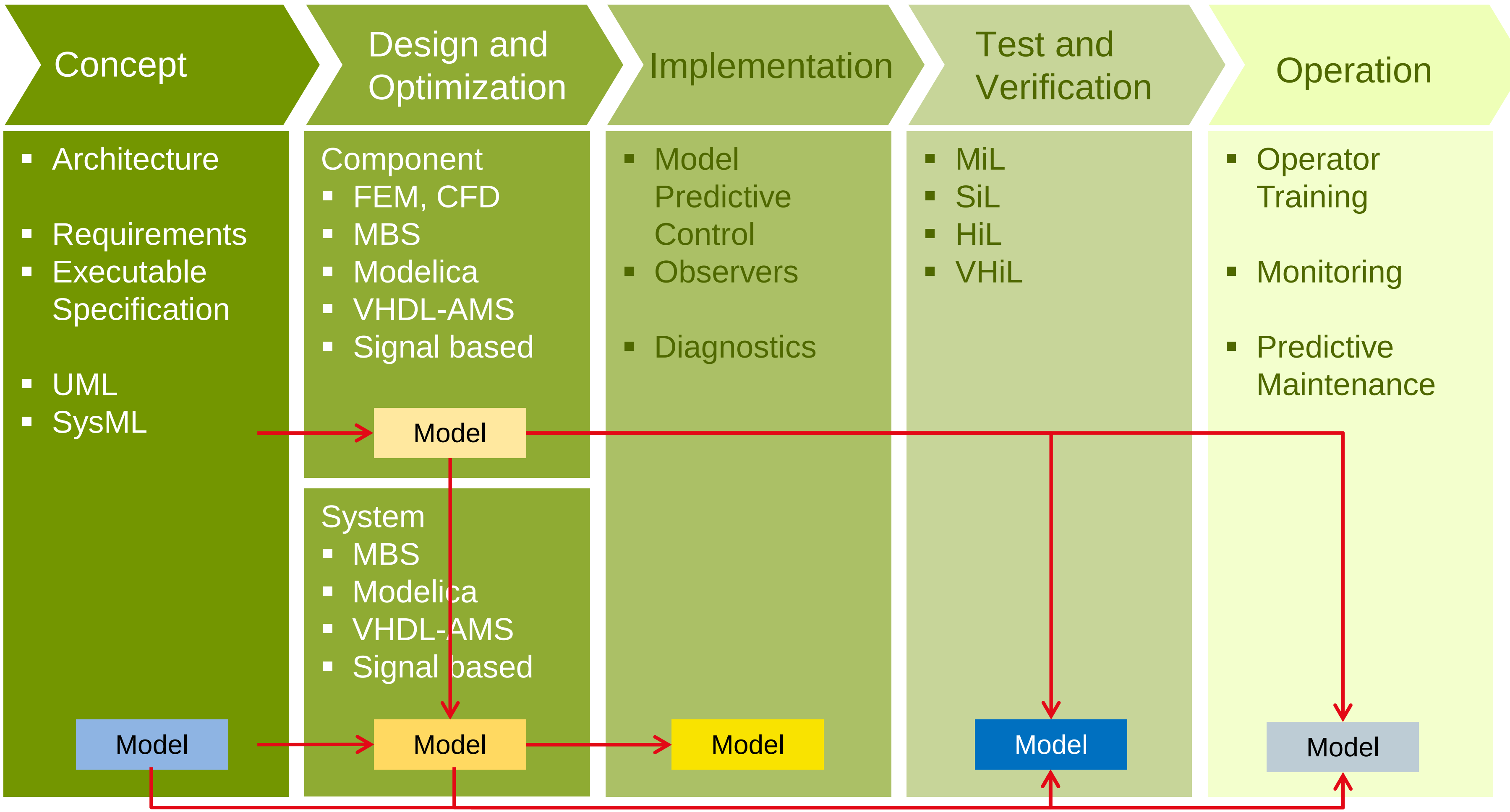
Contents

Where are we now?

Motivation



Concept
Design and Optimization
Implementation
Test and Verification
Operation
Architecture
Requirements
Executable Specification
UML
SysML
Component
FEM, CFD
MBS
Modelica
VHDL-AMS
Signal based
System
MBS
Modelica
VHDL-AMS
Signal based
Model Predictive Control
Observers
Diagnostics
MiL
SiL
HiL
VHiL
Operator Training
Monitoring
Predictive Maintenance
Model
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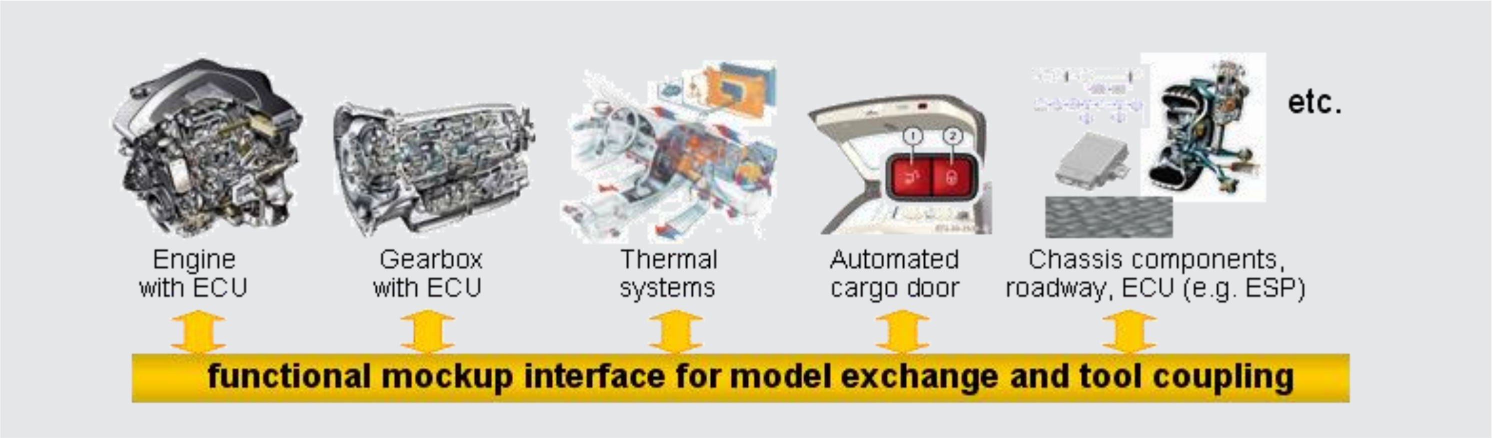
Motivation



Challenges for Functional Mock-up:

- Different tools and languages are involved
- No standards for model interface and co-simulation available
- Protection of model IP and know-how of supplier

Modelisar project:

- Functional Mock-up Interface for Model Exchange and Co-Simulation

Functional Mock-up Interface

EU project Modelisar (2008 – 2011, 26 Mill. €, 178 my)

- Initiated by Daimler AG, 28 European partners
  - Tool vendors
  - Users
  - Research organizations
- Proof of concept in industrial use cases

After 2011

- Continuation as Modelica Association Project
- Modelica Association changed its bylaws to become an umbrella organization for projects related to model based system design

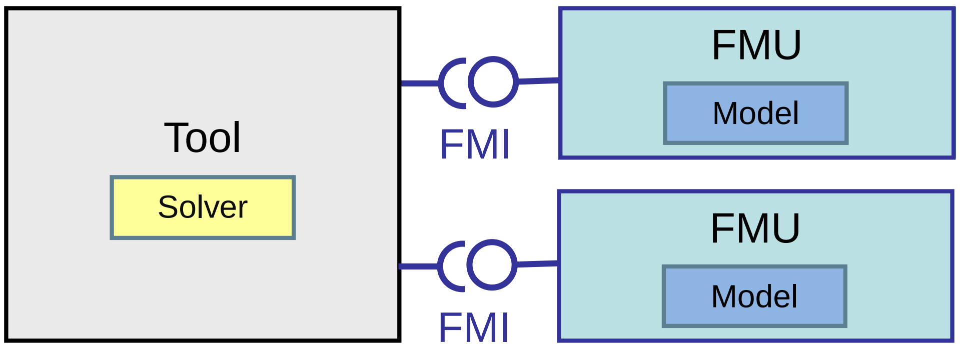
MODELISAR
(ITEA 2 ~ 07006)

Partners

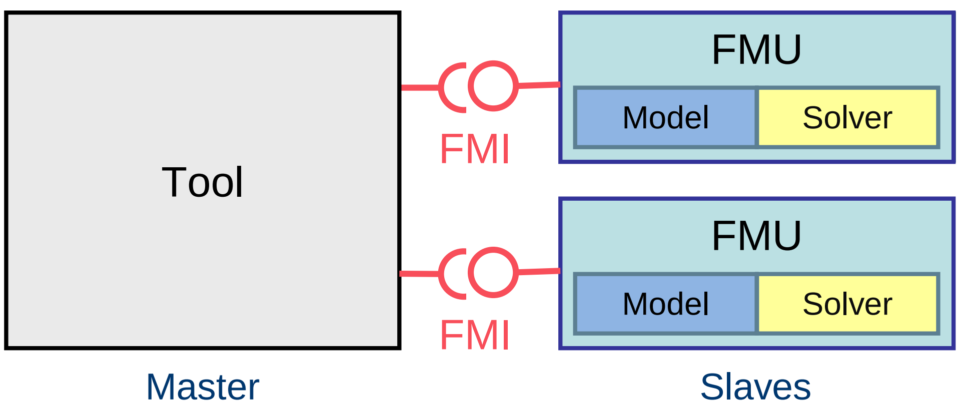
ARMINES
Arsenal Research
ATB
AVL
Berata
Daimler
Dassault Systèmes
David
DLR
Dynasim
Extessy
FhG First, IIS EAS, SCAI
Geensys
Halle University
IFP
Imagine
INSPIRE
SIMPACK AG
ITI
LMS International
QTronic
Schneider Electric
Trialog
Triphase
TWT
Verhaert
Volkswagen
Volvo

FMI – Main Design Idea

- FMI for Model Exchange



- FMI for Co-Simulation

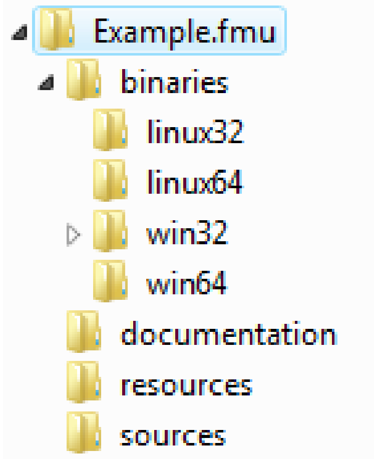


FMI – Main Design Idea

- A component which implements the interface is called a Functional Mockup Unit (FMU)

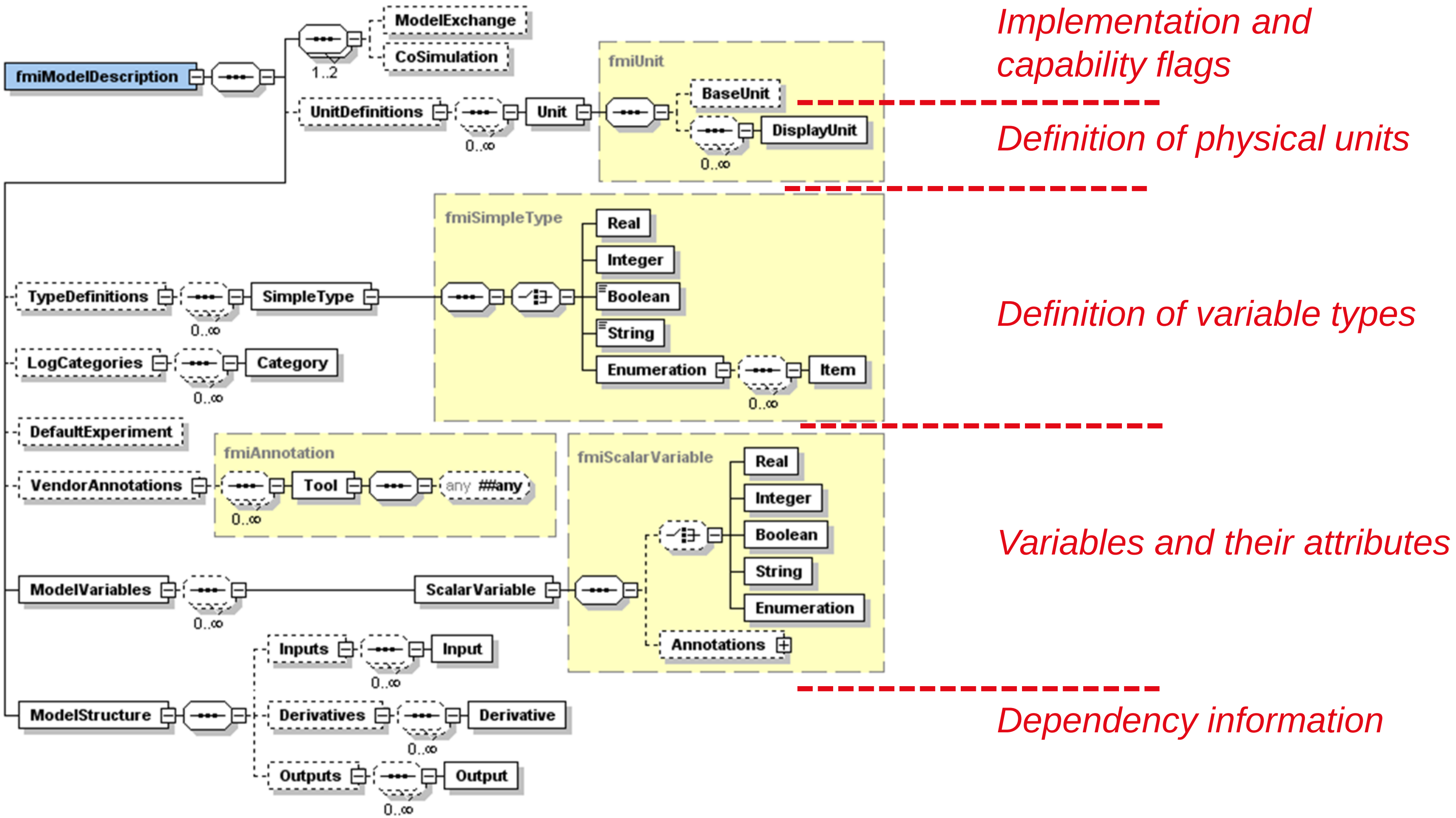
- Separation of:
  - Description of interface data: XML file
  - Functionality: Application Programming Interface (API) in C

- An FMU is a zipped file (*.fmu) containing:
  - modelDescription.xml
  - Implementation in source and/or binary form
  - Additional data and functionality



XML Model Description

Interface definition is stored in an xml-file:



C-Interface

- Instantiation:
```
fmiComponent fmiInstantiate(fmiString instanceName, ...)
```
  - Returns an instance of the FMU. Returned `fmiComponent` is an argument of the other interface functions.
- Functions for initialization, termination, destruction
- Support of real, integer, boolean, and string inputs, outputs, parameters
- `Set` and `Get` functions for each type:
```
fmiStatus fmiSetReal    (fmiComponent c,
                         const fmiValueReference vr[], size_t nvr,
                         const fmiReal value[])
fmiStatus fmiSetInteger(fmiComponent c,
                         const fmiValueReference vr[], size_t nvr,
                         const fmiInteger value[])
```
- Identification by `valueReference`, defined in the XML description file for each variable

FMI for Model Exchange

- Functionality of state of the art modeling methods can be expressed
- Support of continuous-time and discrete-time systems
- Model is described by differential, algebraic, discrete equations

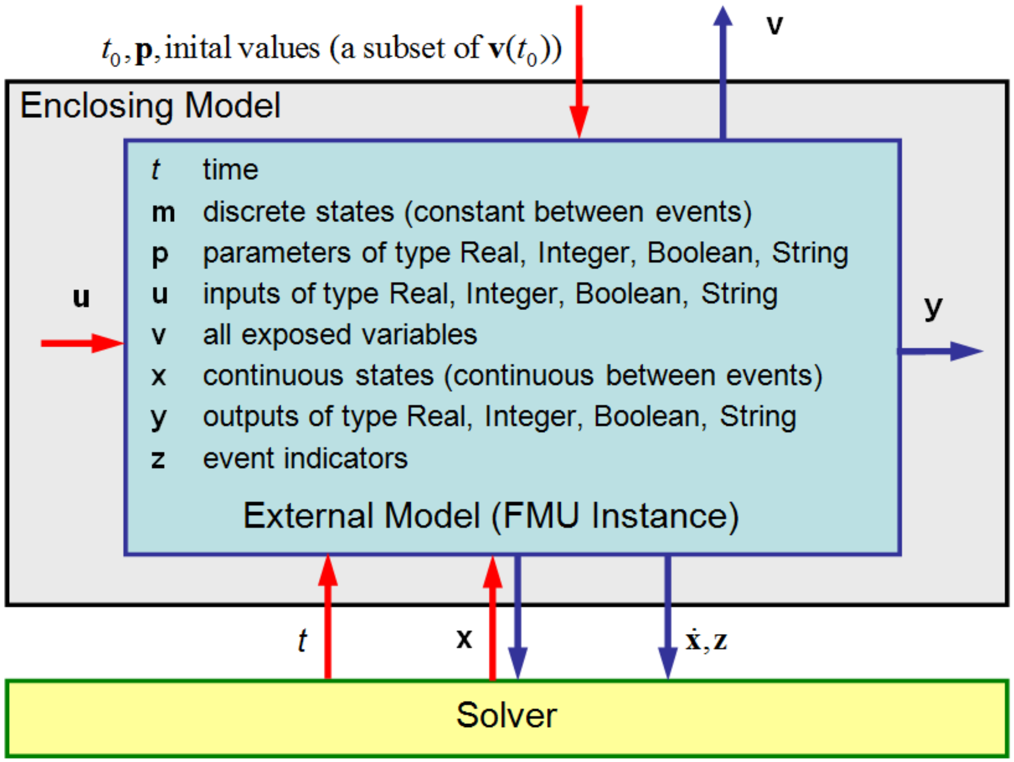
- Interface for solution of hybrid Ordinary Differential Equations (ODE)
- Handling of time, state and step events, event iteration

- Discarding of invalid inputs, state variables

- No explicit function call for computation of model algorithm
  - FMU decides which part is to be computed, when a `fmi2GetXXX` function is called
  - Allows for efficient caching algorithms

FMI for Model Exchange

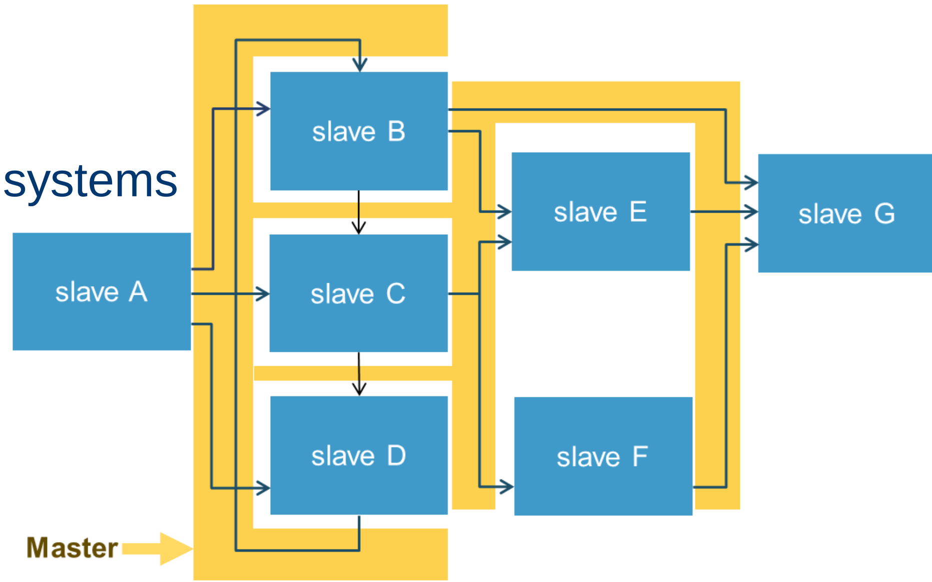
Exchanged data:



Co-Simulation

Motivation

- Simulation of heterogeneous systems
- Partitioning and parallelization of large systems
- Multirate integration
- Hardware-in-the-loop simulation



Definition:

- Coupling of several simulation tools
- Each tool treats one part of a modular coupled problem
- Data exchange is restricted to discrete communication points
- Subsystems are solved independently between communication points

FMI for Co-Simulation

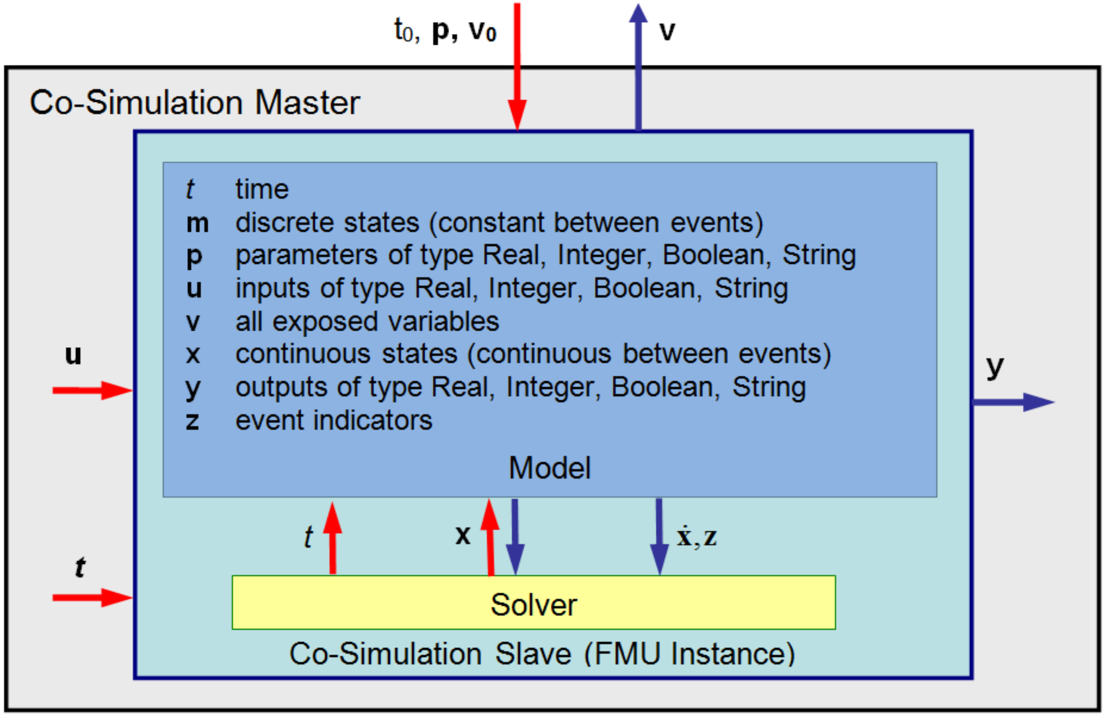
- FMI enables sophisticated Co-Simulation Master Algorithms:
  - Optional variable communication step size
  - Optional higher-order approximation of inputs and outputs
  - Optional repetition of communication steps
- Capabilities of the slave are contained in the XML-file
- Master can decide which coupling algorithm is applicable

➡ Tools which do not support all features are not excluded

- Asynchronous execution (allows for parallel execution)

FMI for Co-Simulation

Exchanged data:

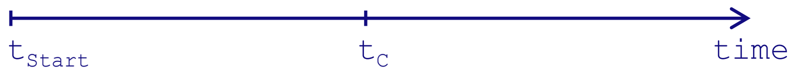


Additional:

- Status information
- Derivatives of inputs, outputs w.r.t. time for support of higher order approximation between communication steps

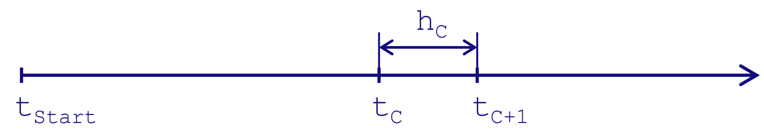
FMI for Model Exchange and Co-Simulation

- Model Exchange:
  (One model evaluation)




```
/* Set inputs*/
fmiSetReal(m, id_u, u, nu);
fmiSetTime(m, tC);
fmiSetContinuousStates(m, x, nx);
/* Get outputs*/
fmiGetReal(m, id_y, y, ny);
fmiGetDerivatives(m, derx, nx);
fmiGetEventIndicators(m, z, nz);
```

- Co-Simulation:
  (One communication step)




```
/* Set inputs*/
fmiSetReal(s, id_u, u, nu);
/* Do computation*/
fmiDoStep(s, tC, hC, fmiTrue);
/* Get outputs*/
fmiGetReal(s, id_y, y, ny);
```

FMI Releases

FMI 1.0

- FMI for Model Exchange: January 2010
- FMI for Co-Simulation: October 2010

FMI 2.0

- Unification and harmonization of Model Exchange and Co-Simulation
- Clarification and improvement of specification document
- Improvement of usability
- Performance improvement for large models
- Release: July 2014

FMI 1.0.1

- No new features, only corrections and clarifications
- Release: July 2017

Tools supporting FMI

See http://fmi-standard.org/tools/

- All fields of modelling and simulation
- All development stages
- Test and verification
- Optimization

Some statistics:

FMI Tools	2011	2012	2013	2014	2015	2017	2018
Support	15	32	37	47	80/42	87/52	108
Planned		9	7	10	6	8	6

During MODELISAR project,
partners and non-partners

Where do we go?

Current Activities

Maintenance Release:

- No new features, but corrections and clarifications
- FMI 2.0.1: in development

FMI 3.0:

- 6 FMI Working Groups develop new features
- Alpha Features List was published in December 2017
- FMI Change Proposals are harmonized after FMI Design Meeting (April $4^{th}/5^{th}$ at ESI ITI in Dresden, Germany)
- Test implementations can start

FMI 3.0 Alpha Feature List

Ports and Icons:

- Help the user to build consistent systems from FMUs and render the systems more intuitively with better representation of structured ports (for instance busses and physical connectors) in the `modelDescription.xml`.
- Group inputs and outputs to connectors
- Define some semantics for support of `flow` and `stream` variables
- Allow the definition of a graphical representation for FMUs and connectors

Array variables:

- Allow FMUs to communicate multi-dimensional variables and change their sizes using structural parameters.
- New `fmi2Get/Set` functions for multidimensional variables

FMI 3.0 Alpha Feature List

Clocks and Hybrid Co-Simulation

- Introduces clocks for synchronization of variables changes across FMUs
- Co-Simulation with events:
  - Early return from `fmi2DoStep` in case of an event,
  - Introduction of Event mode similar to Model Exchange to support event iteration and super dense time

Binary Data Type:

- Adds an opaque binary data type to FMU variables to allow, for instance, efficiently exchanging of complex sensor data.
- Data is exchanged via an array of `char`
- Semantics of the data is defined by a MIME type

FMI 3.0 Alpha Feature List

Intermediate Output Values (FMI for Co-Simulation):

- Allow access to intermediate output values between communication time points from the FMU to disclose relevant subsystem behavior for analysis or advanced co-simulation master algorithms.
- Every time a co-simulation slave finishes an internal time step it calls a callback function. In this function variables can be retrieved via `fmi2GetXXX` function calls.

Source code FMUs:

- Adding more information to the modelDescription.xml file to improve automatic import and compilation of source code FMUs.

FMI is great, but not magic!

FMI is great: Why we love it!

- Standardized, open, vendor-neutral API
- Convenient container for handling simulation artefacts: storing, sharing, archiving…
- Free simulation users from modeling/generation tool knowledge
- Reduce IP sharing

- A new quality of simulation is attainable now, because:
  - Producing, sharing and using simulation components is simpler than ever
  - Coupling multi-disciplinary simulations is now more efficient than ever

Before FMI

With FMI

What we want

FMI is great: But not magic!

- Implementation quality is a continuous effort: new tools, new standard versions
- License issues: license-free generation? Digital rights managements?
- Numeric challenges remain:
  - Splitting systems into components increases numeric problems
  - Pressure towards Co-Simulation: simpler handling, but time delays introduce errors
  - Still based on floating point numeric: (a + b) + c != a + (b + c)
  - Stability and speed of simulations still depend on solver technology
- We need to educate users and management
  - Experts are still needed
  - Goals need to stay realistic

Before FMI

With FMI

What some of us get

Some Use Cases

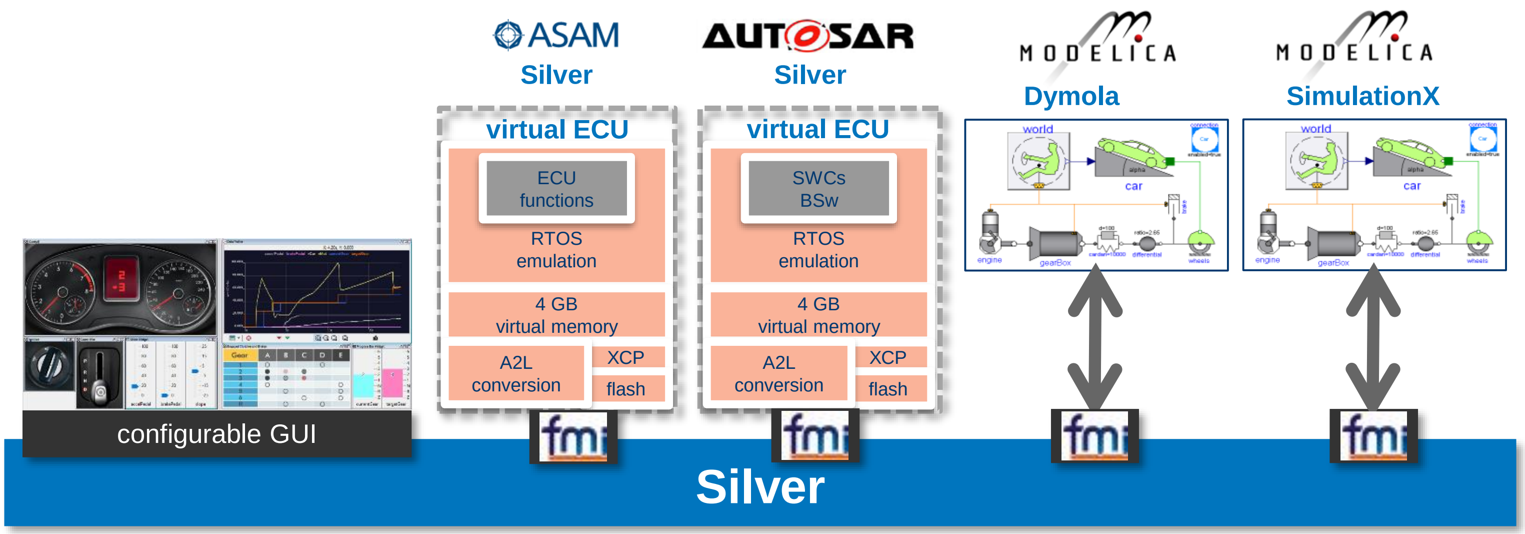
FMI Use Cases: Automotive Industry

FMI usage is state of the art in automotive industry:

- OEMs and suppliers exchange FMUs (power train and chassis components) for integration of components to system models
- FMUs are integrated in engine test benches for real drive emission tests
- FMUs are integrated in Software-in-the-Loop and Hardware-in-the-Loop application for test and verification

FMI Use Cases:
Development in Automotive Control Software

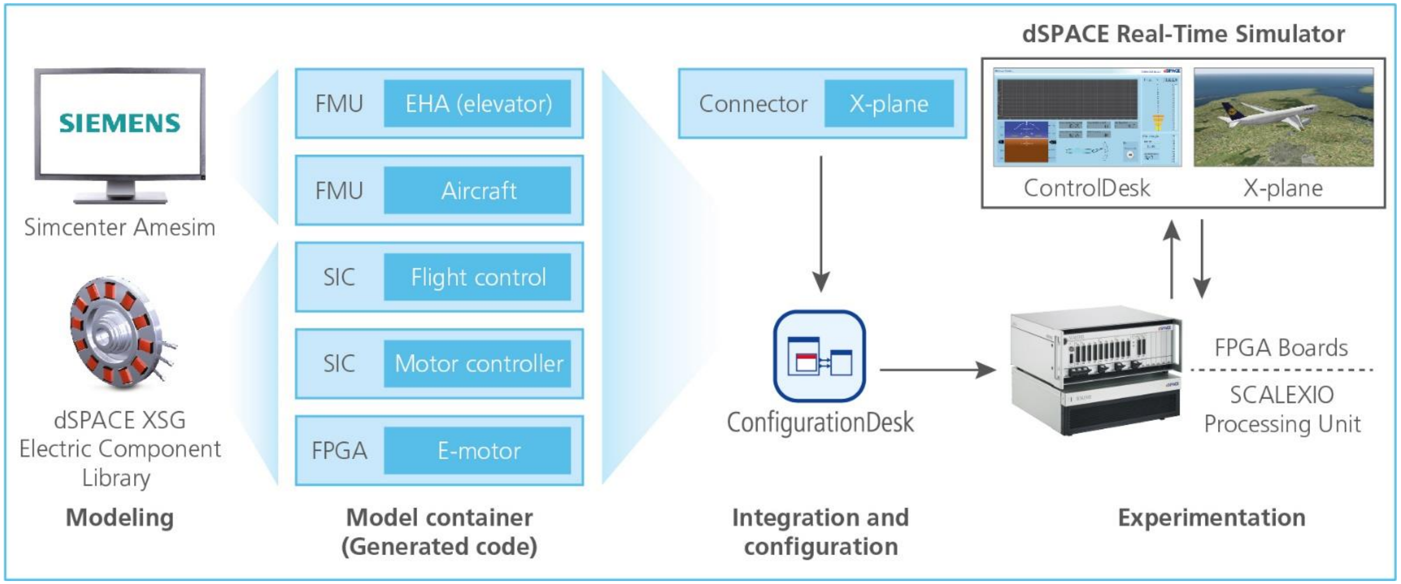
Engineers develop controllers with virtual systems combined of FMUs from different sources, e.g. Silver, SimulationX, Dymola,…



- Read more: E. Chrisofakis et. al.: *Simulation-based development of automotive control software with Modelica.* 8th International Modelica Conference, 20-22.03.2011, Dresden, Germany http://qtronic.de/doc/SiL_at_Daimler_2011.pdf

FMI Use Cases: Aerospace Industry

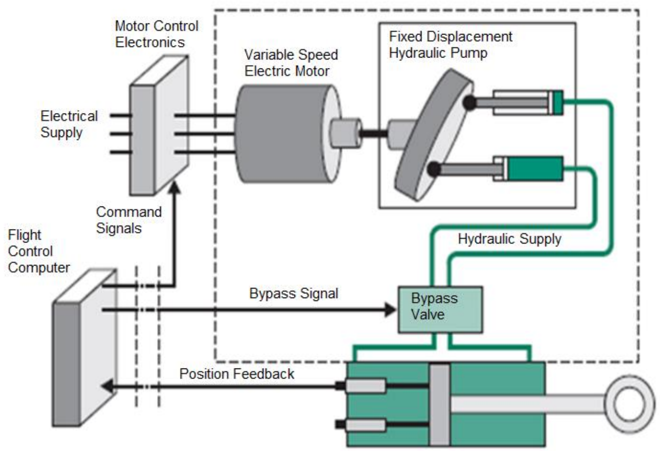
Simcenter Amesim FMUs are integrated with dSPACE SCALEXIO for real-time simulation and test:

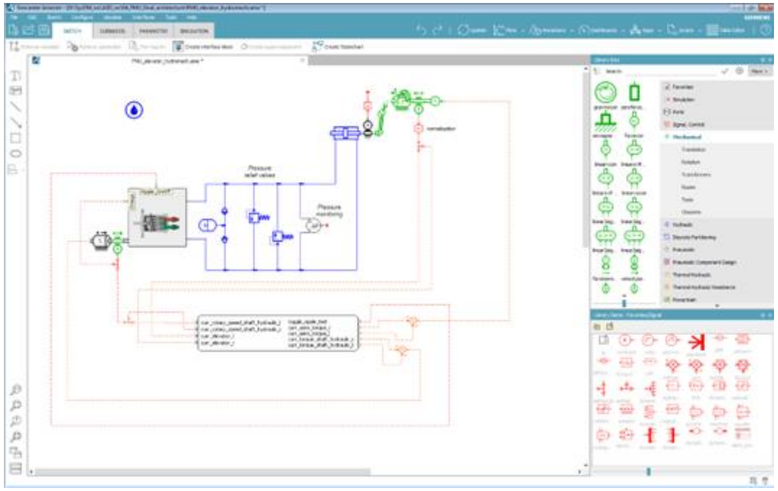


- Read more: “Using FMI- and FPGA-Based Models for the Real-Time Simulation of Aircraft Systems” 2018 AIAA Modeling and Simulation Technologies Conference https://arc.aiaa.org/doi/10.2514/6.2018-0125

FMI Use Cases: Aerospace Industry

Real-time capable model of electro hydraulic actuator in Simcenter Amesim:

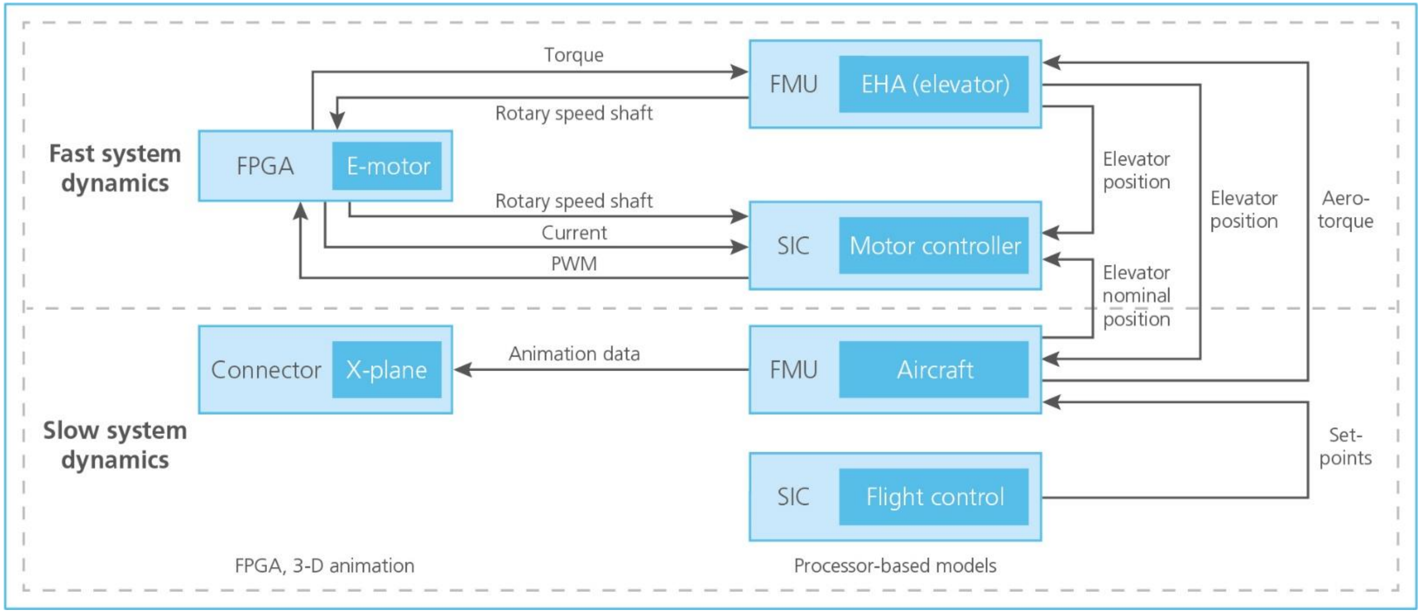




FMI Use Cases: Aerospace Industry

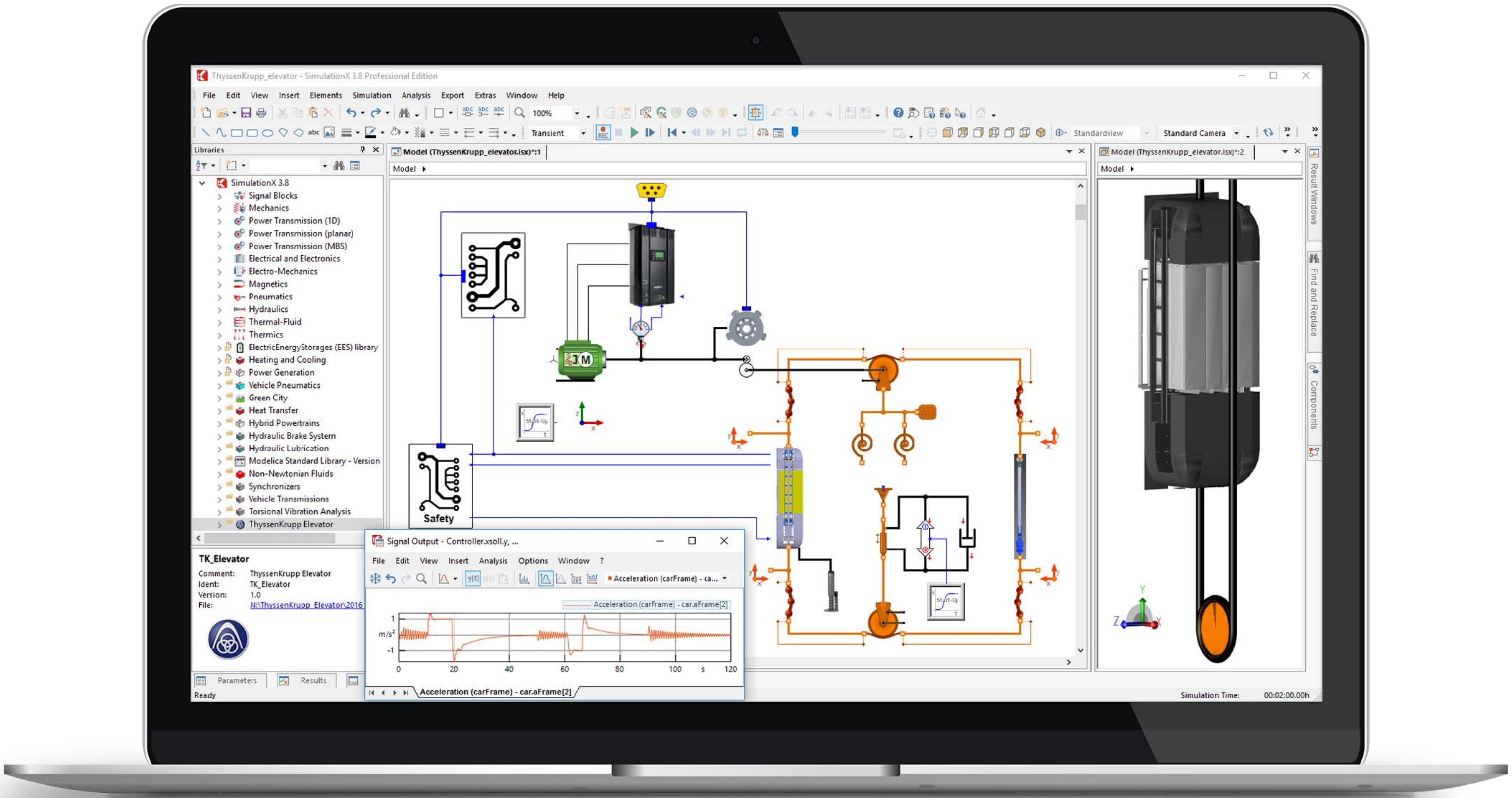
The whole system in dSPACE SCALEXIO:

- Combination of FPGA based models and processor based models created from various model sources
- Models created via dSPACE XSG Electric Component Library, MathWorks Simulink, Siemens Simcenter Amesim



FMI Use Cases: Industry

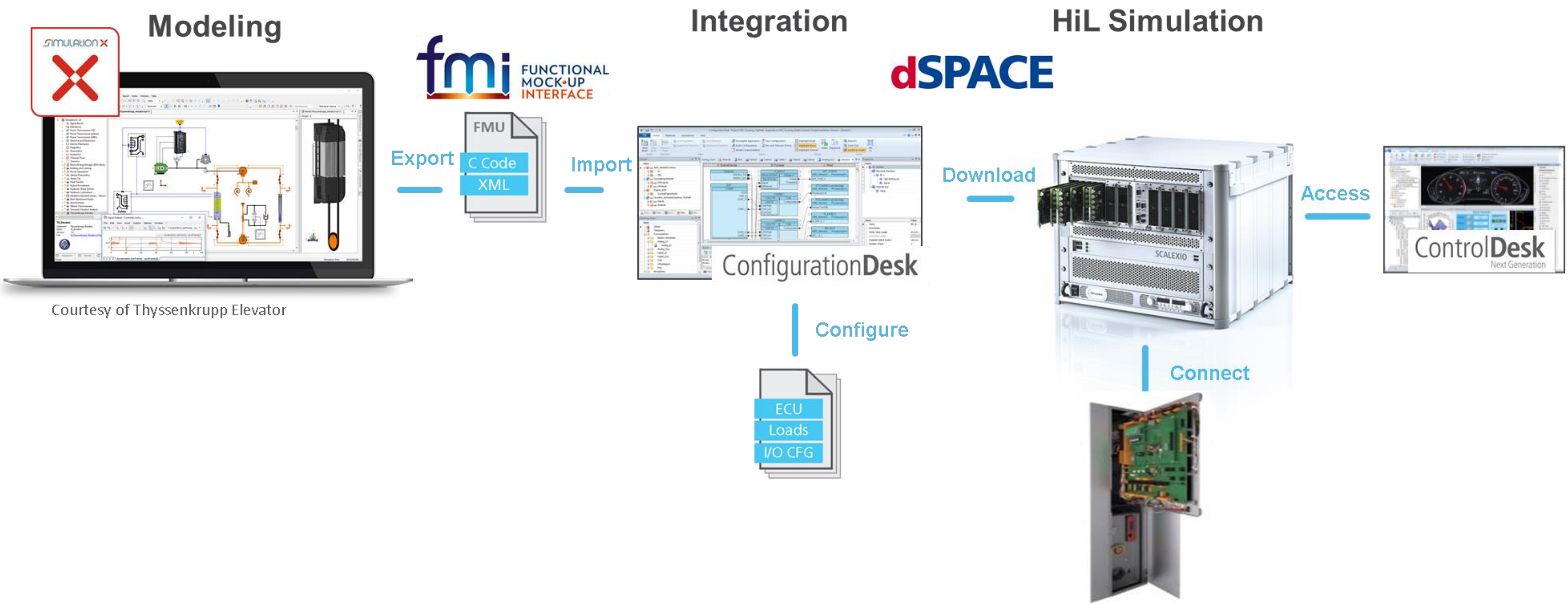
Model-in-the-loop strategy for control development:



Courtesy of Thyssenkrupp Elevator

FMI Use Cases: Industry

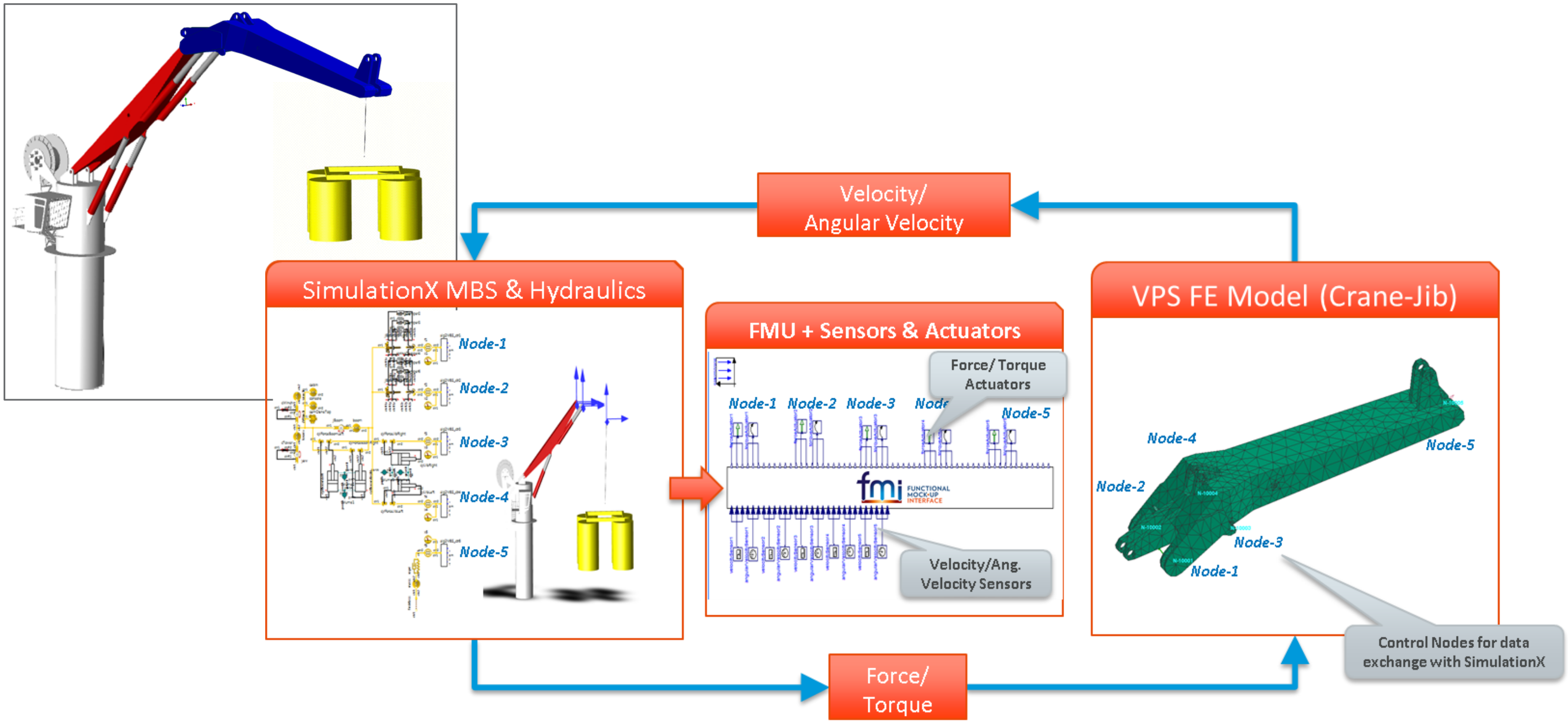
Hardware-in-the-loop strategy for elevator systems:



- Read more:“Efficient safeguarding of elevator functionalities through virtual commissioning” ProSTEP iViP Symposium 2017
  http://www.prostep-ivip-symposium.org/fileadmin/Veranstaltungen/symposium17/Presentations/Presentation_Aloth_ESI-ITI.pdf

FMI Use Cases: FEM and system simulation

Coupling of SimulationX actuators and VPS FE model for loading of a crane to capture realistic and dynamic stress strain effects:



Related Research Projects

Research Projects, related to Modelica and FMI

ACOSAR (2015-2018):

- Advanced Co-Simulation Open Software Architecture
- https://itea3.org/project/acosar.html

EMPHYSIS (2017-2020):

- Embedded Systems with Physical Models in the Production Code Software (https://itea3.org/project/emphysis.html)
- Standard for integration of code (in different levels) in ECUs

EMBrACE (in preparation):

- Environment for model-based rigorous adaptive co-design and operation of CPS (https://itea3.org/project/embrace.html)
- Specification of a common requirements modelling language, so that requirements can easily be understood by all stakeholders whatever their domain of expertise

Research Projects, related to Modelica and FMI

PEGASUS (2016-2019):

- Establishment of Generally Accepted Quality Criteria, Tools and Methods as well as Scenarios and Situations for the Release of Highly-automated Driving Functions
- Standardized Interface for Sensor Simulation
  => Open Simulation Interface (OSI)
  https://github.com/OpenSimulationInterface/open-simulation-interface
- Packaging of Sensor models into FMUs
  => OSI Sensor Model Packaging (OSMP) – Binary Variables
  https://github.com/OpenSimulationInterface/osi-sensor-model-packaging
- http://www.pegasus-projekt.info/en/

ACOSAR

Facts

Framework:	ITEA3 (Call1)
Duration:	09/2015 – 08/2018
Overall Budget:	7.9 M€
Countries:	AT, DE, FR; 16 Partners
Coordinator:	VIRTUAL VEHICLE (AT)
Website:	www.acosar.eu

Objective:

- Tool independent standard to simplify integration of RT and non-RT systems

Motivation:

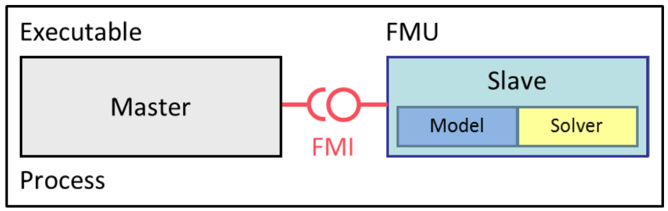
- Efficient integration of heterogeneous test systems
- Tool neutral integration of distributed co-simulation
- 9 Automotive use-cases

Plan:

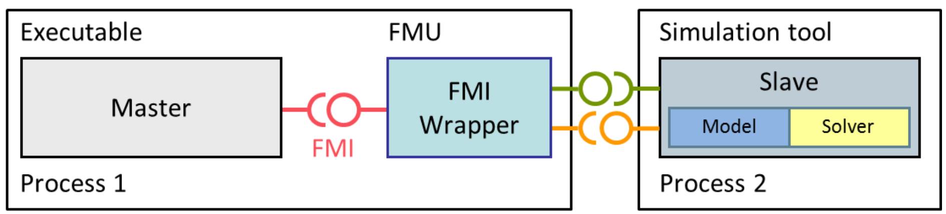
- Transfer the result to the Modelica Association and maintain the standard within a Modelica Association Project in parallel to FMI

FMI Architectures

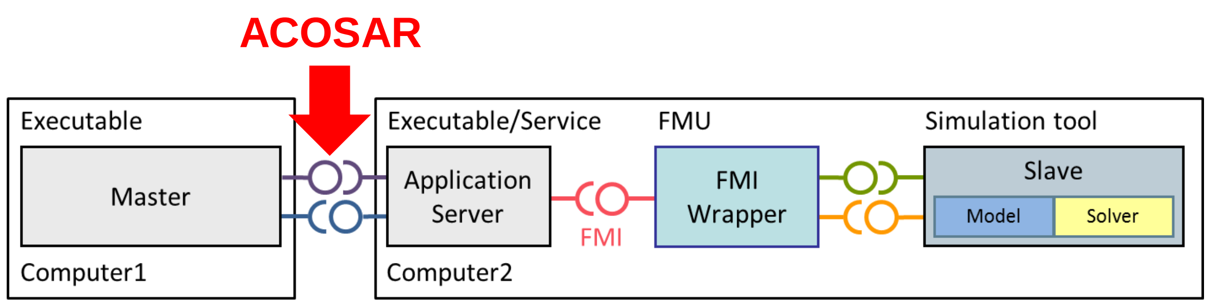
- Standalone:



- Tool Based:



- Distributed:



ACOSAR Approach

Distributed Co-Simulation Protocol (DCP):

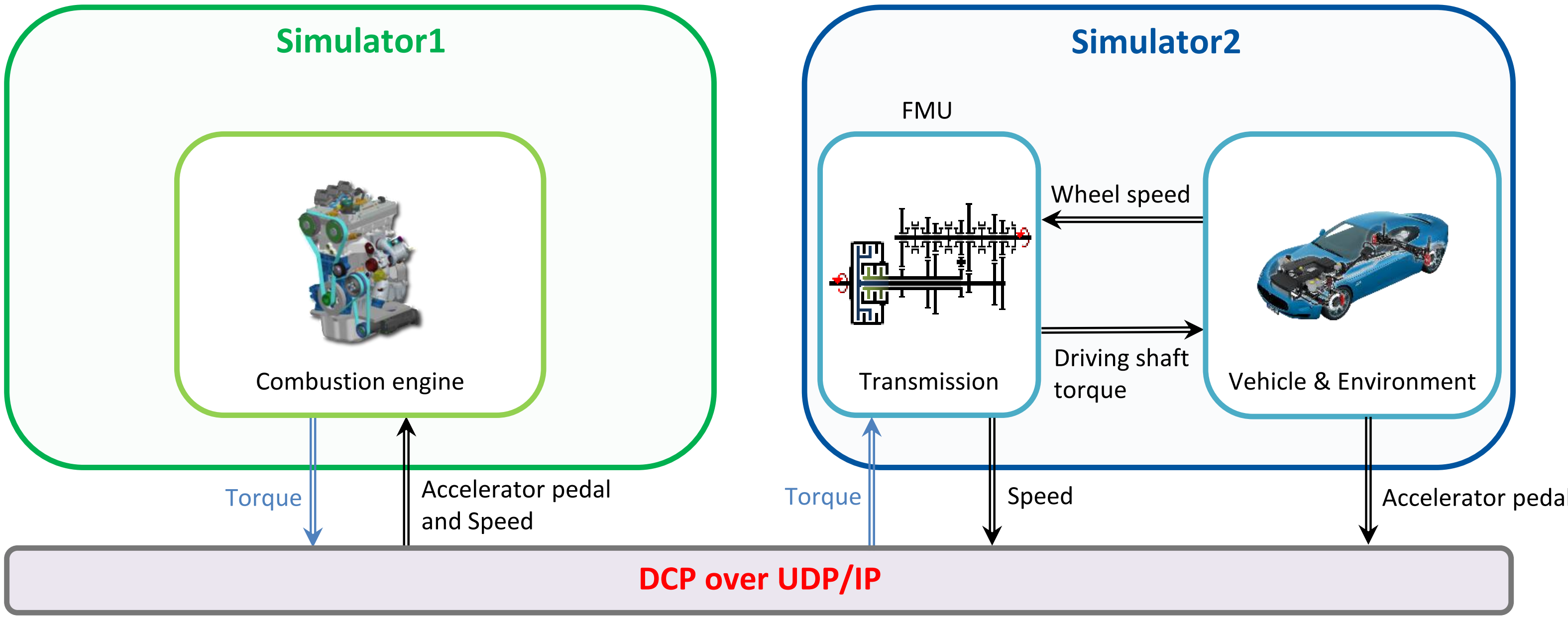
- Network protocol is defined for different media (UDP, TCP/IP, EtherCAT, USB, Bluetooth)
- A DCP-Slave is described by an XML file (similar to FMI modelDescription)
- Same data types as in FMI (Real, Integer, Boolean, String, Binary, multi-dimensional) are supported
- Semantics of co-simulation is consistent to FMI for Co-Simulation
- Realtime and non-realtime co-simulation is supported

Enables:

- Distributed tool based interactive Co-Simulation
- Connection of test benches and simulation models

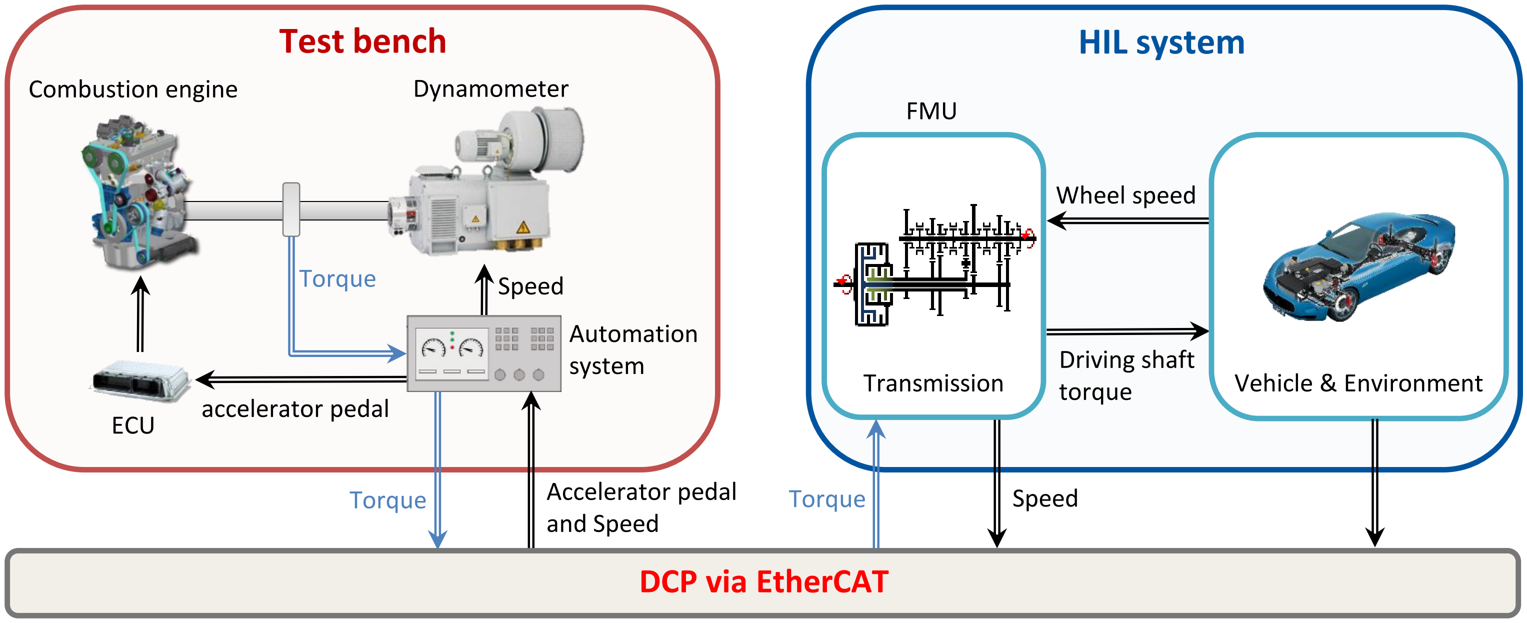
ACOSAR Use Cases

Non-real time Co-Simulation:



ACOSAR Use Cases

Real time Co-Simulation:



Organizational Structure

Project Rules

General conditions

- Results are owned by the Modelica Association (MA)
- Results are freely available under a copyleft license
- Contributors must sign Corporate Contributor License Agreement (CCLA)
- FMI MAP members need not to be MA members
- Meetings are open to the public

FMI Steering Committee

- Defines FMI policy, strategy, feature roadmap, releases
- Voting rights
- Bosch, Dassault Systèmes, dSPACE, ESI ITI, IFP EN, MapleSoft, Modelon, QTronic, Siemens

FMI Advisory Committee

- Contribute to FMI design
- Access to FMI infrastructure (repository, trac, meeting minutes)
- AVL, Armines, DLR, IBM, ETAS, Fraunhofer (IIS/EAS, First, SCAI), Open Modelica Consortium, Synopsys, TWT, University of Halle

Current Activities

Quality of tool implementations

- **FMI Cross Check Rules**
- Continuous maintenance of **FMI Compliance Checker**

Improvement of processes

- Adaption of FMI Project Rules to the current status
- **Definition of FMI Development Process**
- **Coordination of FMI Working Groups**

Public relations

- FMI is a registered trademark in Europe
- FMI logo is publicly available
- Rearrangement and new content of website (download, FAQ)

Resources

Website: fmi-standard.org

- FAQ
- Download specifications
- List of tools and cross check results

Ambiguities in specification, feature requests etc.:

- Public error tracking system trac.fmi-standard.org
- Send e-mail to contact@fmi-standard.org
- Contact your FMI-tool vendor

Mailing lists:

- FMI-Info, used for public announcements, subscribe via contact page
- FMI-Design, for active developers, send e-mail to contact@fmi-standard.org

Conclusions

- FMI is a unique initiative for Model Exchange and Co-Simulation
- Tool independent
- Developed in close cooperation between leading European CAE tool vendors
- Proof of concept in industrial use cases during development
- Fast adoption by tool vendors (100+ tools with FMI support)
- Used in industry and research
- Open and free access to FMI specification and additional material
- Continued maintenance and development as Modelica Association Project