Designing and Implementing Field Agents with IEC 61499 and 4diac

IEC 61499 Reference Model for Distributed Industrial Automation

[1]Thomas I. Strasser and [2]Alois Zoitl

[1]AIT Austrian Institute of Technology and TU Wien, Vienna, Austria
[2]Johannes Kepler University Linz, Linz, Austria

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June 24-28, 2024, Bilbao School of Engineering, Universidad del País Vasco, Bilbao, Spain

IEC 61499 Lecture

	Monday (24/06)	Tuesday (25/06)	Wednesday (26/06)	Thursday (27/06)	Friday (28/06)
8:00 – 9:30	Opening				
9:30 – 11:00	Introduction to industrial agents (part I)	Design and assessment of Cyber-physical Systems (part I)	Designing and implementing field agents with IEC 61499 and 4diac (part I)	Methodological support for asset integration and AAS development based on reference architectures	Microservice-based Industrial Agents: Managing manufacturing applications through the Edge-Fog-Cloud continuum
11:00 – 11:30	COFFEE BREAK				
11:30 – 13:00	Introduction to industrial agents (part II)	Design and assessment of Cyber-physical Systems (part II)	Designing and implementing field agents with IEC 61499 and 4diac (part II)	Research keynote (I) Design of agent based customizable and resilient I4.0 Platforms – CTC Research keynote (II) Robotic grasping decision making assisted by AI and simulation – Tekniker	Advances in Practical Applications of Agents, Multi-Agent Systems
13:00 – 14:30	LUNCH				
14:30 – 16:00	Multi-agent programming (part I): Fundamentals	Multi-agent programming (part II): Gateway Agent: A customization mechanism for asset integration	Industry keynote (I) Digitalisation in a glass manufacturing industry - Vidrala	Industry visit (I) Factory Lab: Testing the orchestration of manufacturing processes with real workpieces and real demands – SMARTPM	Closing
16:00 – 16:30	COFFEE BREAK				
16:30 – 18:00	Pitch presentations of participants PhD projects or research lines	Multi-agent programming (part III): IEEE 2660.1-2020: Asset integration practices	Industry keynote (II) Application of container-based virtualization technologies to smart grid architectures – Ingeteam	Industry visit (II) MIC platform: Intelligent orchestration of autonomous and flexible manufacturing processes – SMARTPM	
19:00 – 20:00			Social event (guided tour of Bilbao)		
20:00 – 22:00				Joint dinner	

Goal of the Lecture

- Overview of interaction patterns for agents with industrial automation devices
- Overview of the IEC 61499 model for distributed, reconfigurable industrial automation and control
- Basic usage of IEC 61499 for the development of field level agents
- Modelling of simple examples
- Overview of realized examples from different domains
- Discussion and questions

About the Speaker – Thomas I. Strasser

- 2001 MSc Industrial Engineering, TU Wien
- 2003 PhD Mechanical Engineering, TU Wien
  Researcher at PROFACTOR (senior researcher since 2007)
- 2010 AIT Austrian Institute of Technology
  Centre for Energy – Electric Energy Systems (senior scientist since 2012)
- 2017 Habilitation (venia docendi), TU Wien
- Scientific co-ordination and WP leader in several national (FIT-IT, FFG, RSA) and international research projects (FP6, FP7, H2020, HEU)
- Active in IEEE (IES, SMCS, PES), CIGRE (SC B5), IEC (TC 65), ÖVE (MR 65)
- Docent for automation at TU Wien
- Current research: power utility automation in smart grids, development of design and validation methods for power system/smart grid applications

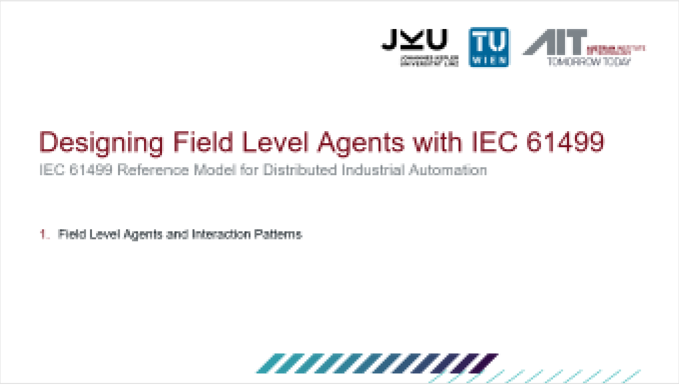
About the Speaker – Alois Zoitl

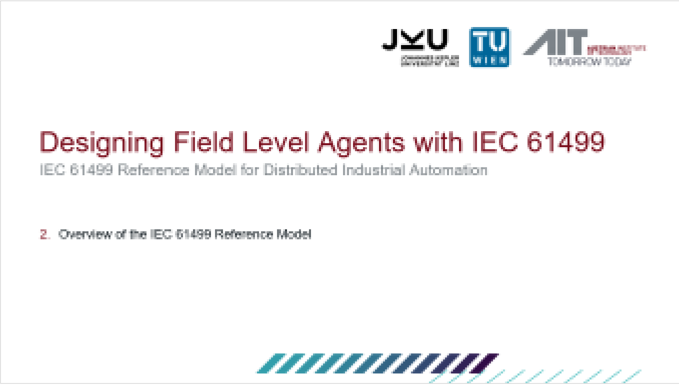
- 2002 MSc Electrical Engineering, Vienna University of Technology, Vienna
  Researcher Automation and Control Institute
- 2003 Automation and Control Institute, Vienna University of Technology, Vienna
  Head of Research, Odo Struger Laboratory
- 2007 PhD Electrical Engineering, Vienna University of Technology, Vienna
- 2012 fortiss GmbH, Munich, Research Group Leader Industrial Automation
- 2015 Convenor IEC TC65B/WG15: IEC 61499
- 2018 Johannes Kepler University Linz, Prof. Cyber-Physical Systems for Engineering and Production
- Core research topics
  - Flexible adaptive production systems
  - Real-time reconfigurable control architectures
  - Software engineering approaches for industrial control applications
  - Distributed control architectures, IEC 61499

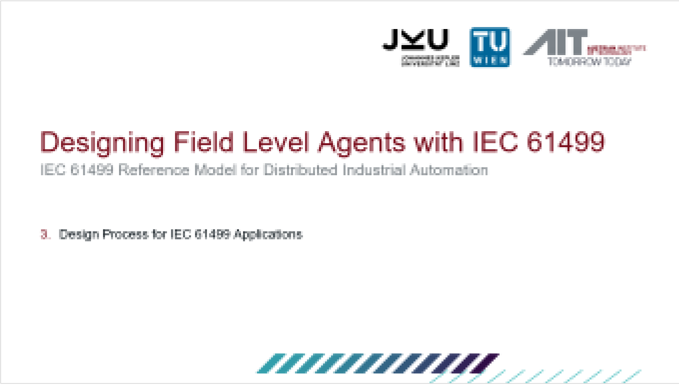
Content of the Lecture

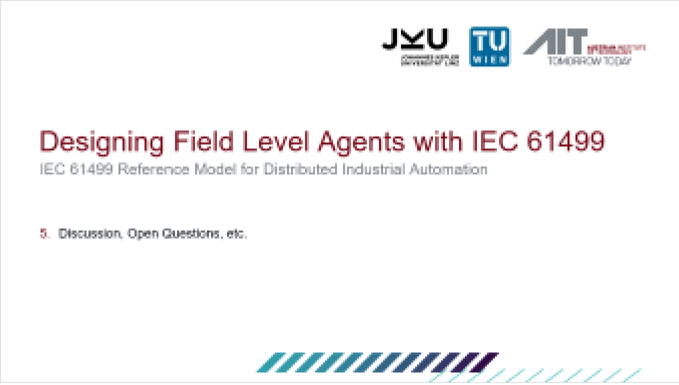
1. Field level agents and interaction patterns
2. Overview of the IEC 61499 reference model
3. Design process for IEC 61499 applications
4. Selected examples
5. Discussion, open questions, etc.
6. Related literature and references

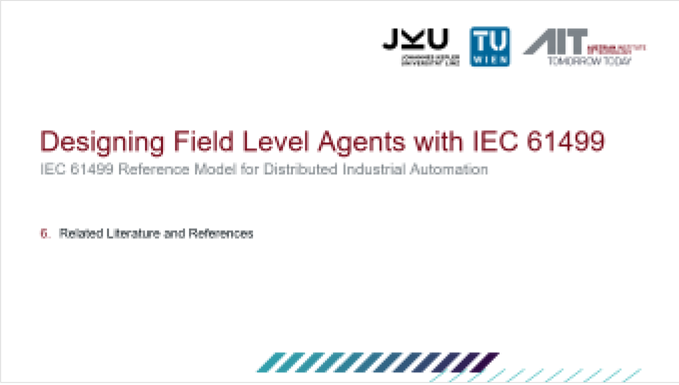
Content of the Lecture











Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

1. Field Level Agents and Interaction Patterns

Field Level Agents and Interaction Patterns

- Multi-Agent Systems (MAS) in industrial environments
  - Suitable to design large scale distributed control systems in a more natural way
  - Provide intelligence, flexibility, robustness, self-adaptation and self-organization
  - Play an important role in realization of Cyber-Physical System (CPS)

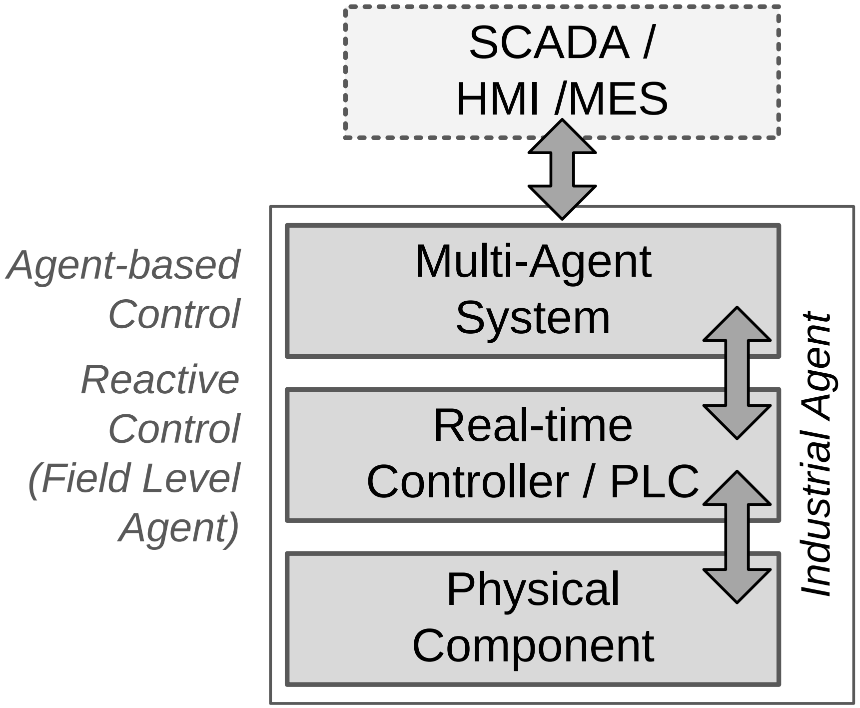
  → ***Usage of industrial agents***
- Industrial Agents
  - Inherit the software agent principles
  - Face industrial requirements
  - Agents usually have associated a physical hardware counterpart

  → ***Increases their deployment complexity!***

Field Level Agents and Interaction Patterns

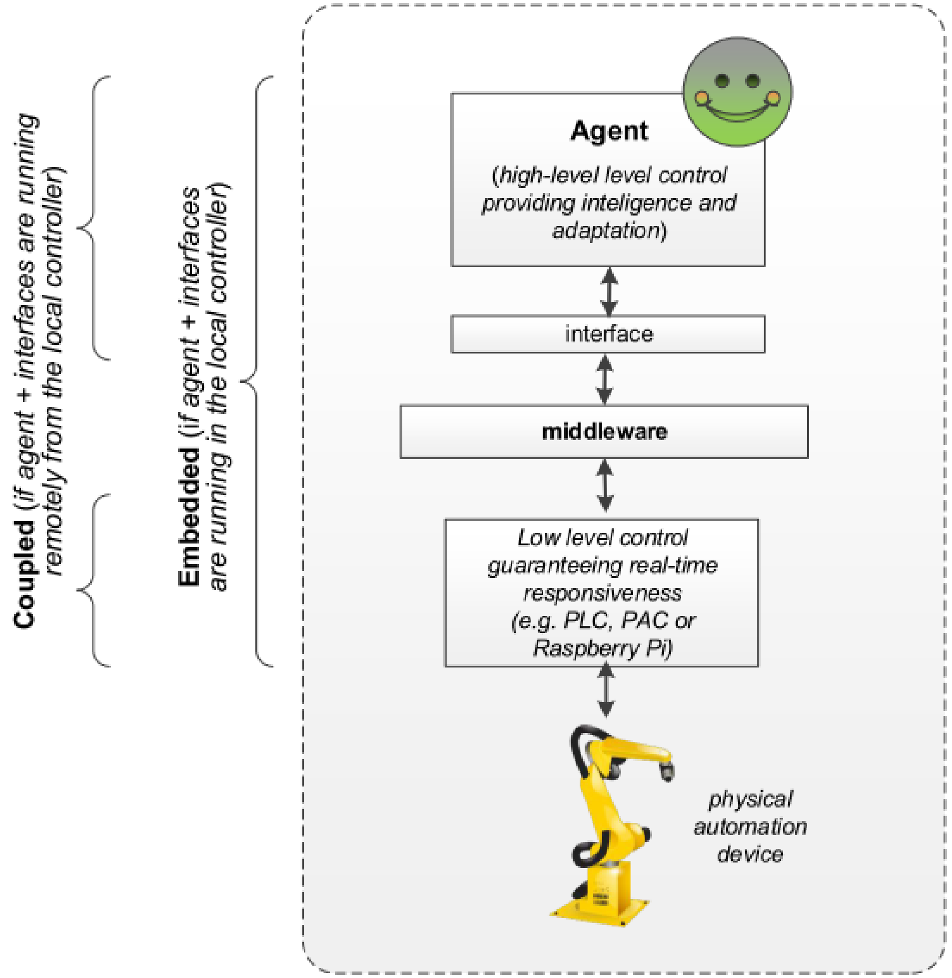
- Typical architecture for industrial agents
  - Usage of a two-layer architecture
    - Agent Control Layer:
      strategic decisions, planning, etc.
    - Reactive Control Layer:
      realization of (real-time) automation / control functions

    → ***Field Level Agents***



Field Level Agents and Interaction Patterns

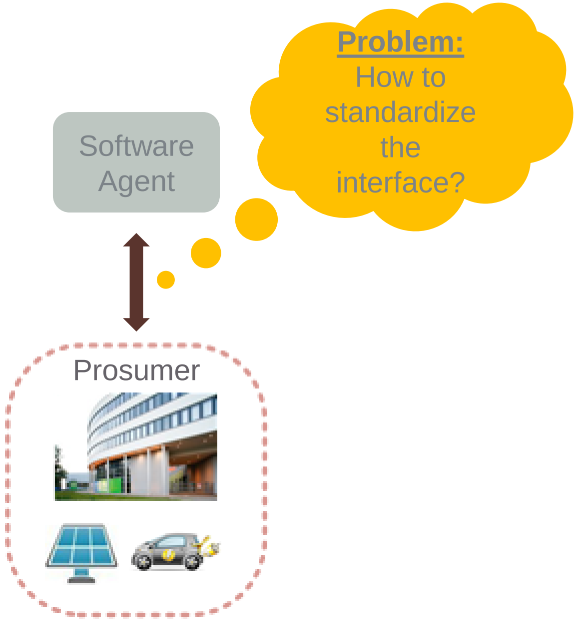
- Illustrating example



Source: P. Leitão, J. Barbosa, "Building a Robotic Cyber-Physical Production Component", SOHOMA'15, Cambridge, UK, 2015.

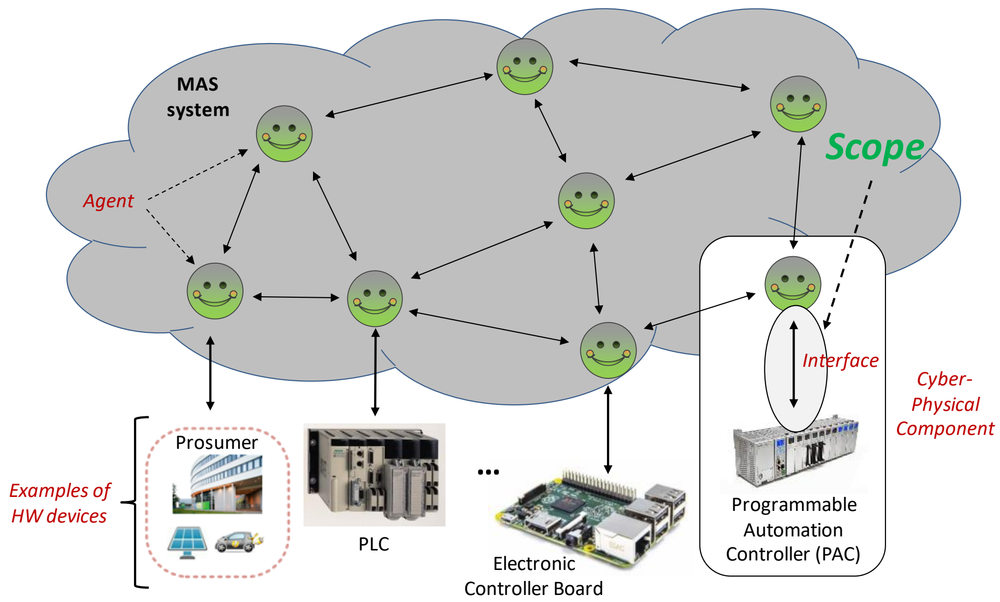
Field Level Agents and Interaction Patterns

- Problem
  - How is the interface between agents and automation functions defined?
  - Several possibilities to realize the automation level, which are typically based on proprietary technologies
- Challenge
  - Achieve full interoperability by a standardized way of information exchange between both layers and invocation of corresponding control level functions
  - Support to engineers to leverage the best practices of developing industrial agents for automation problems and given application fields



Field Level Agents and Interaction Patterns

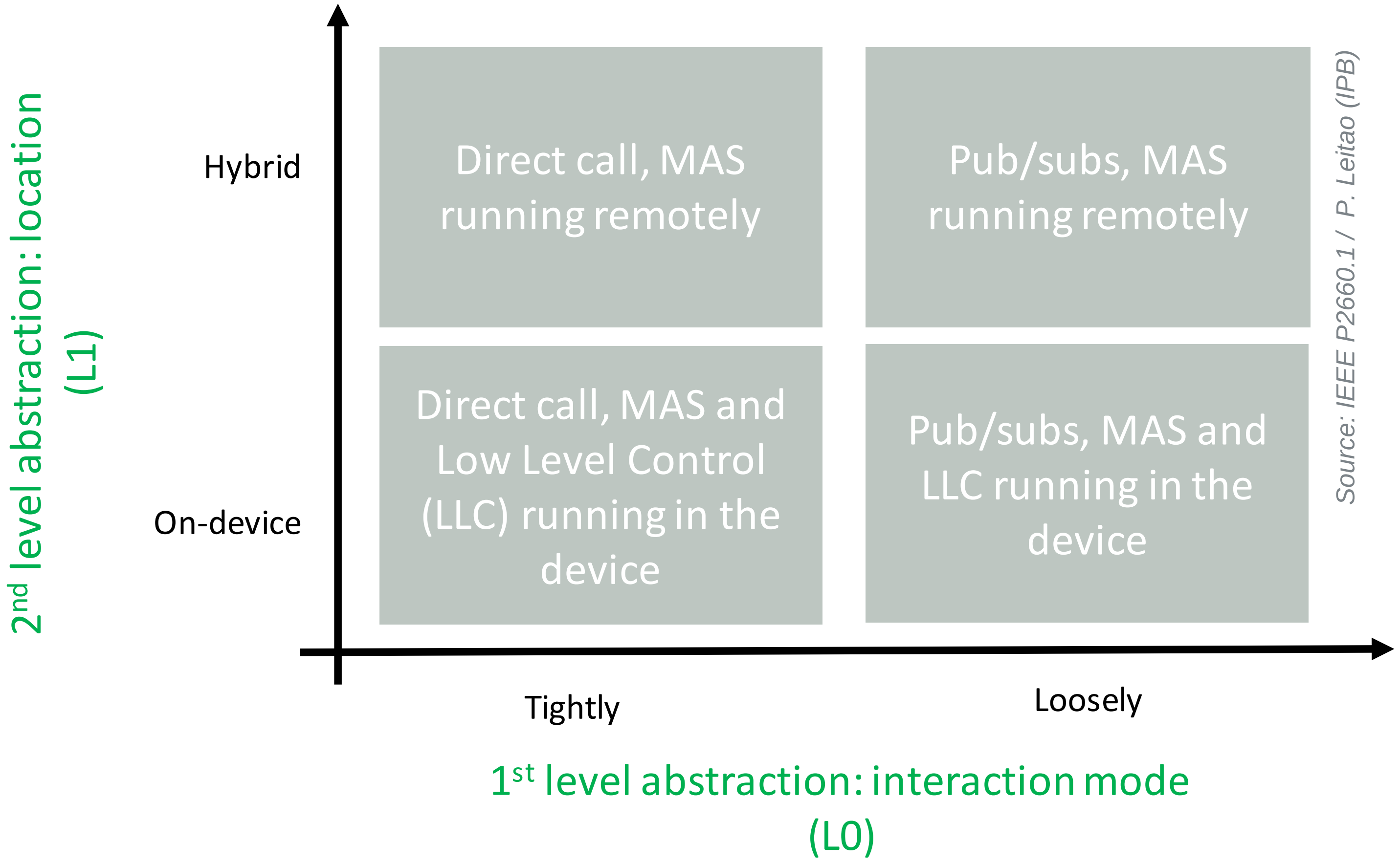
- IEEE P2660.1 integration approach
  - Provision of recommended practices to solve the interface problem when applying Industrial Agents
  - Integrating software agents with automation control level in the context of cyber-physical systems
  - Best practices rules, guidelines and design patterns



Source: IEEE P2660.1 / P. Leitao (IPB)

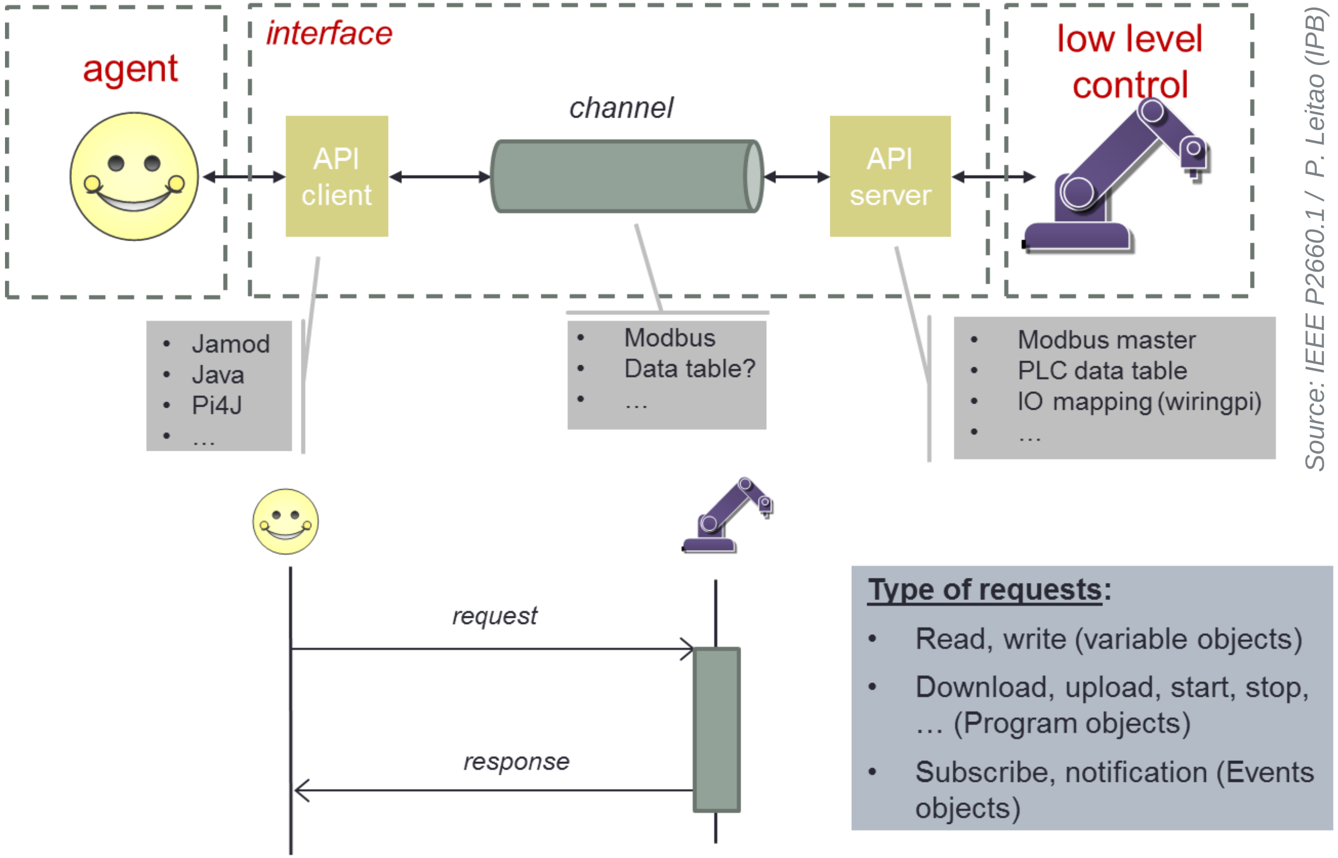
Field Level Agents and Interaction Patterns

- Two main abstraction levels



Field Level Agents and Interaction Patterns

- Practice {Tightly Coupled, Hybrid}



Type of requests:

- Read, write (variable objects)
- Download, upload, start, stop, … (Program objects)
- Subscribe, notification (Events objects)

Field Level Agents and Interaction Patterns

- Potential approaches for realization the low level control
  - Machine code
    - Assembler
  - General (embedded) programming languages
    - C/C++,
    - ADA, etc.
  - Domain-specific languages for industrial automation
    - Function Blocks (FB),
    - Sequential Function Charts (SFC),
    - Structured Text (ST),
    - Ladder Diagram (LD), etc.

Field Level Agents and Interaction Patterns

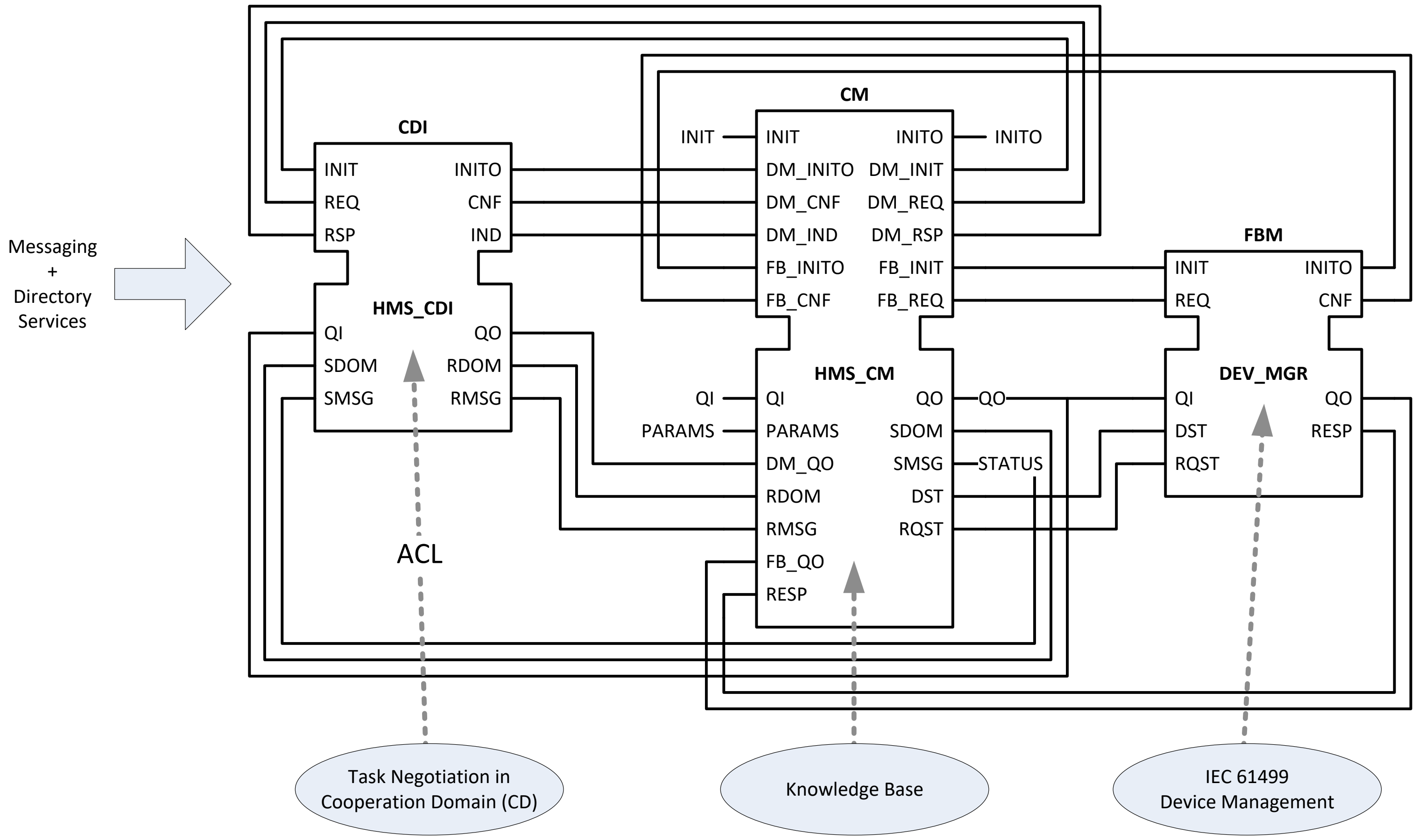
- FBs commonly used concept; two main flavors in industrial automation

IEC 61131-3 ***Programmable Logic Controller (PLC)***	*IEC 61804* ***Distributed Control System (DCS)***
freely programmable	configurable
centralized	distributed

- Alternative approach: IEC 61499
  - Goal IEC 61499: generic FB-based architecture with combined features (programmable, configurable, distributed)
  - Plus: dynamically reconfigurable
  - Feedback to both original standards → not happened so far

Field Level Agents and Interaction Patterns

- Example for interfacing Field Level Agents with IEC 61499



Source: J.H. Christensen, 'HMS/FB architecture and its implementation', in Agent-Based Manufacturing: Advances in the Holonic Approach, ed SM Deen, Springer, Berlin, pp. 53-88.

Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

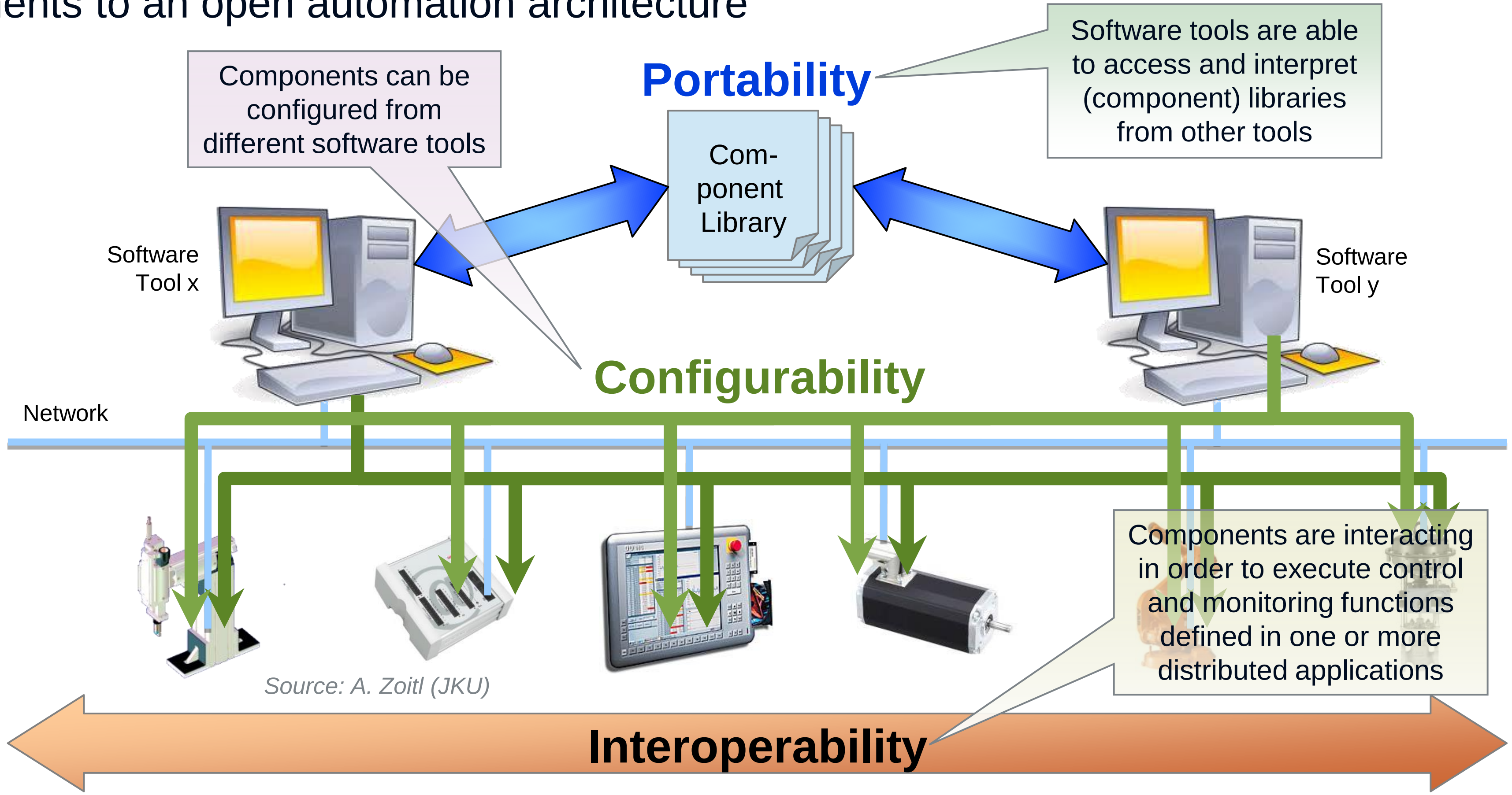
2. Overview of the IEC 61499 Reference Model

Overview of the IEC 61499 Reference Model

- A standard for distributed adaptive automation and control systems
  - Origin
    - 1990s: holonic and agile manufacturing systems
    - Requirements: flexibility, adaptivity, and distribution
  - Goals
    - Open and standardized architecture for Function Blocks (FB) applied in distributed Industrial-Process Measurement and Control Systems (IPMCS)
    - Logical, equal control devices
    - Not necessarily a supervisory control device
    - Basic support for dynamic reconfiguration

Overview of the IEC 61499 Reference Model

- Requirements to an open automation architecture



Autonomous, distributed components (mechatronic, electrical, pneumatic, etc.)

Overview of the IEC 61499 Reference Model

- A standard for distributed adaptive automation and control systems

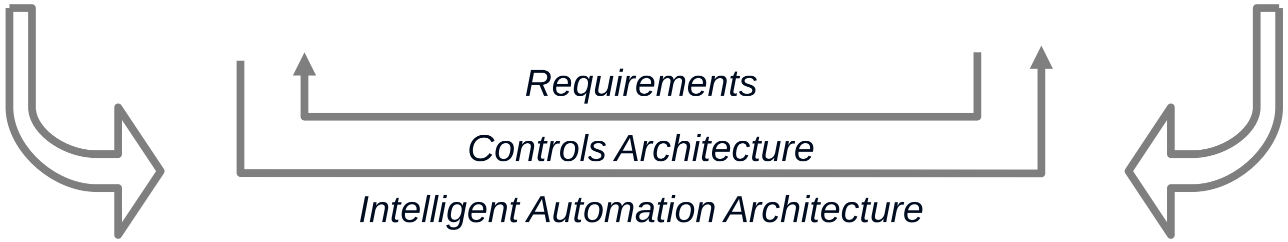
IEC 61499

- *Parent organization:* IEC
- *Working group:* TC65/WG6
- *Goal:* Standard model (function blocks) for control encapsulation & distribution
- *Started:* 10/90
- *Active development:* 3/92
- *Trial period:* 2001-03
- *Completion:* 2005

Holonic Manufacturing Systems (HMS)

- *Parent organization:* IMS
- *Working group:* HMS Consortium
- *Goal:* Intelligent manufacturing through holonic (autonomous, cooperative) modules
- *Feasibility study:* 3/93-6/94
- *First phase:* 2/96 - 6/00
- *Second phase:* 6/00-6/03

Source: HoloBloc (J. Christensen)

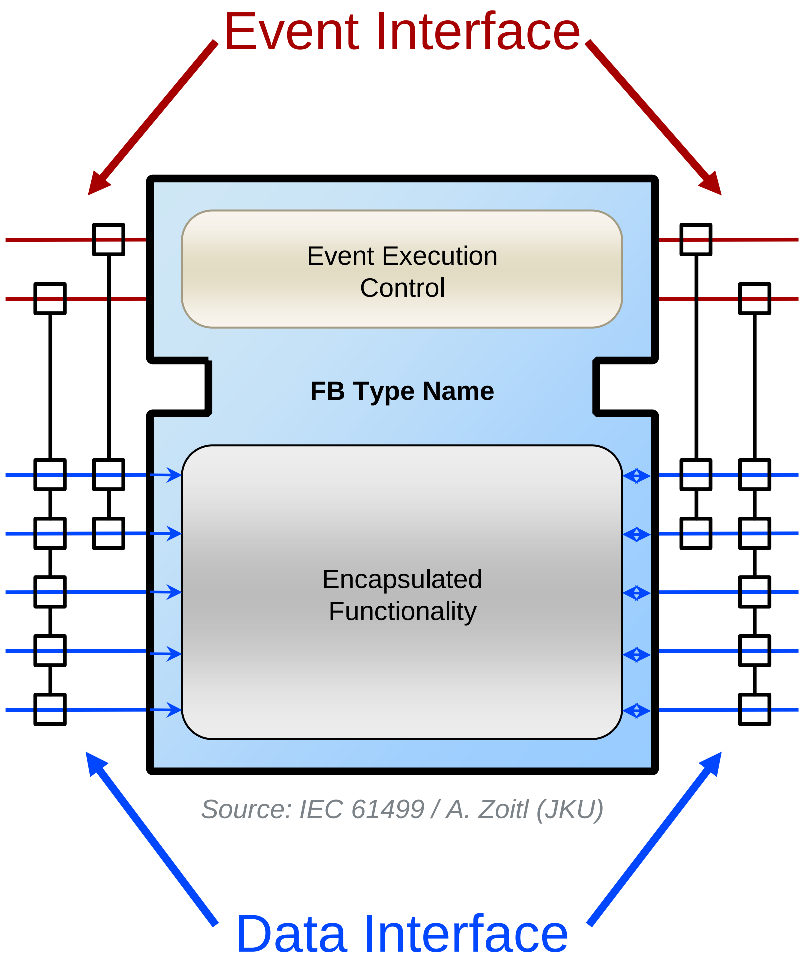


Overview of the IEC 61499 Reference Model

- Status
  - Official name
    - Functions Blocks
  - 1st Ed. published in 2005, 2nd Ed. in 2012/13
  - Currently 3 parts
    - Part 1: Architecture
    - Part 2: Software tool requirements
    - Part 4: Rules for compliance profiles
  - Two further parts in preparation
    - Part 3: Application guidelines (orig. version withdrawn 2008)
    - Part 5: Proposed extensions

Overview of the IEC 61499 Reference Model

- Function Block Model
  - FBs extended with event interface
  - Pure event-driven execution
  - Data types based on IEC 61131-3
  - Focus on encapsulation & reuse
  - No global or directly addressed variables
  - Hardware access with special function block type: *Service Interface Function Block (SIFB)*

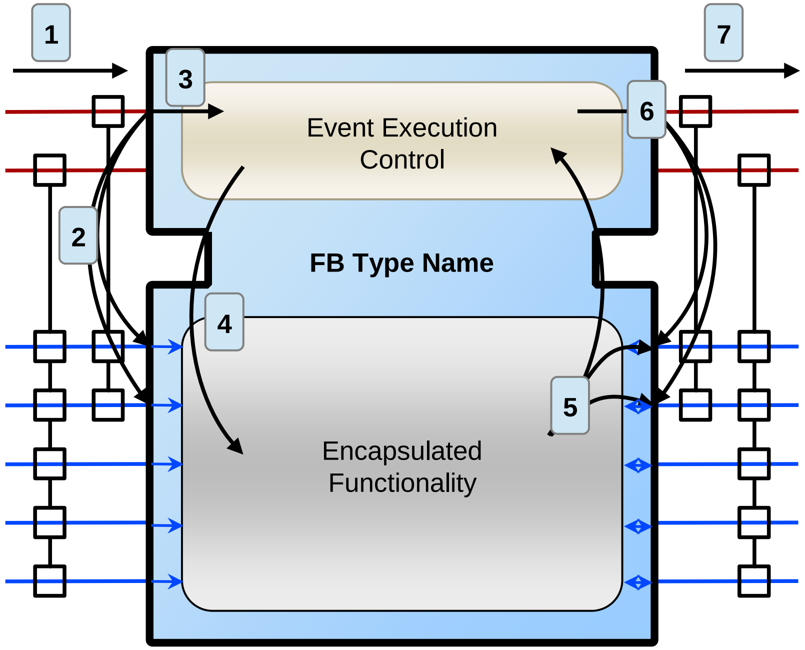


Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

- Execution Model (general FB execution behavior)
  - Input event gets delivered
  - Associated input data sampled
  - Event execution control is notified
  - Internal functionality is triggered for execution
  - Internal functionality finishes execution and provides new output data
  - Output event is ready for sending, associated output data is updated
  - Output event is sent

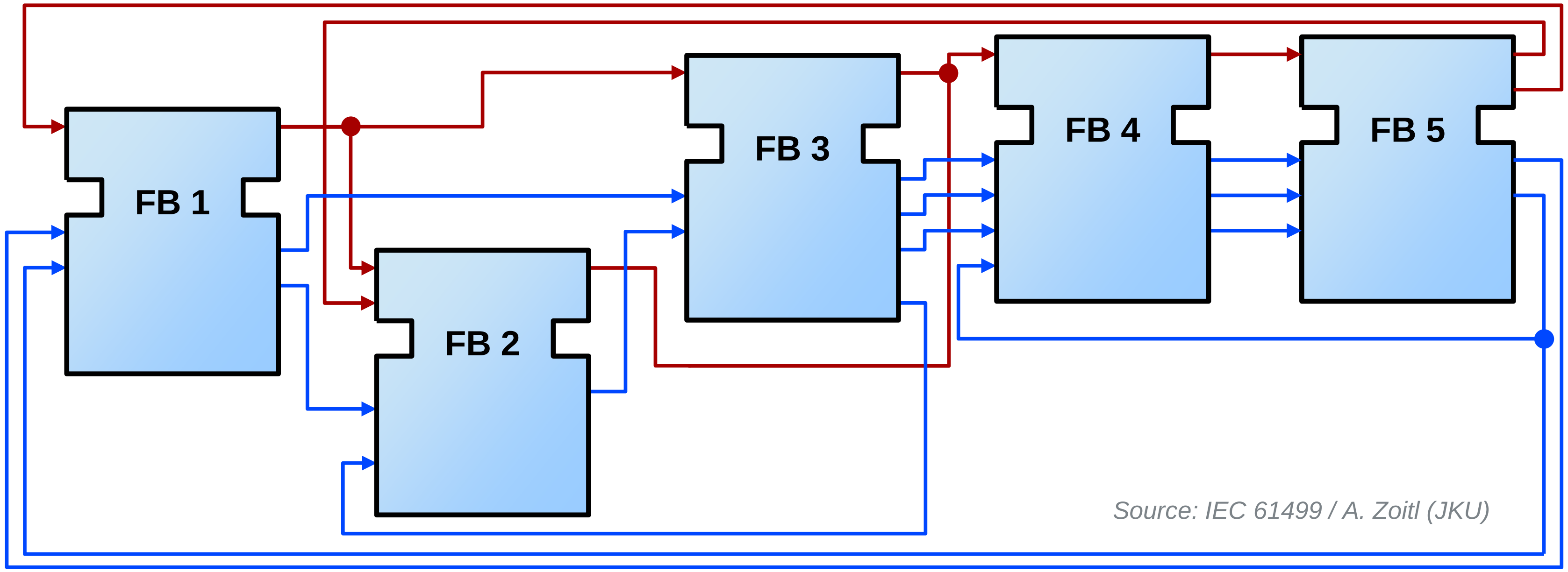
  → ***Step 4 to 7 may repeat several times***



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

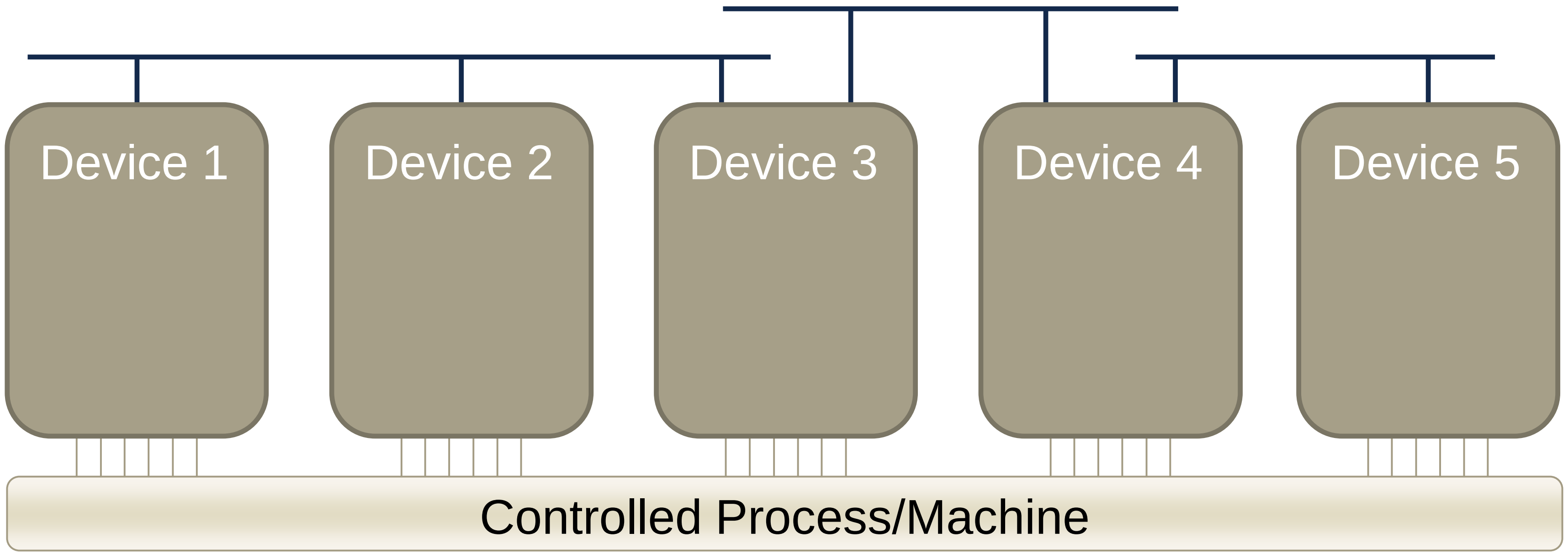
- Application Model
  - Function Blocks
  - Event connections
  - Data connections



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

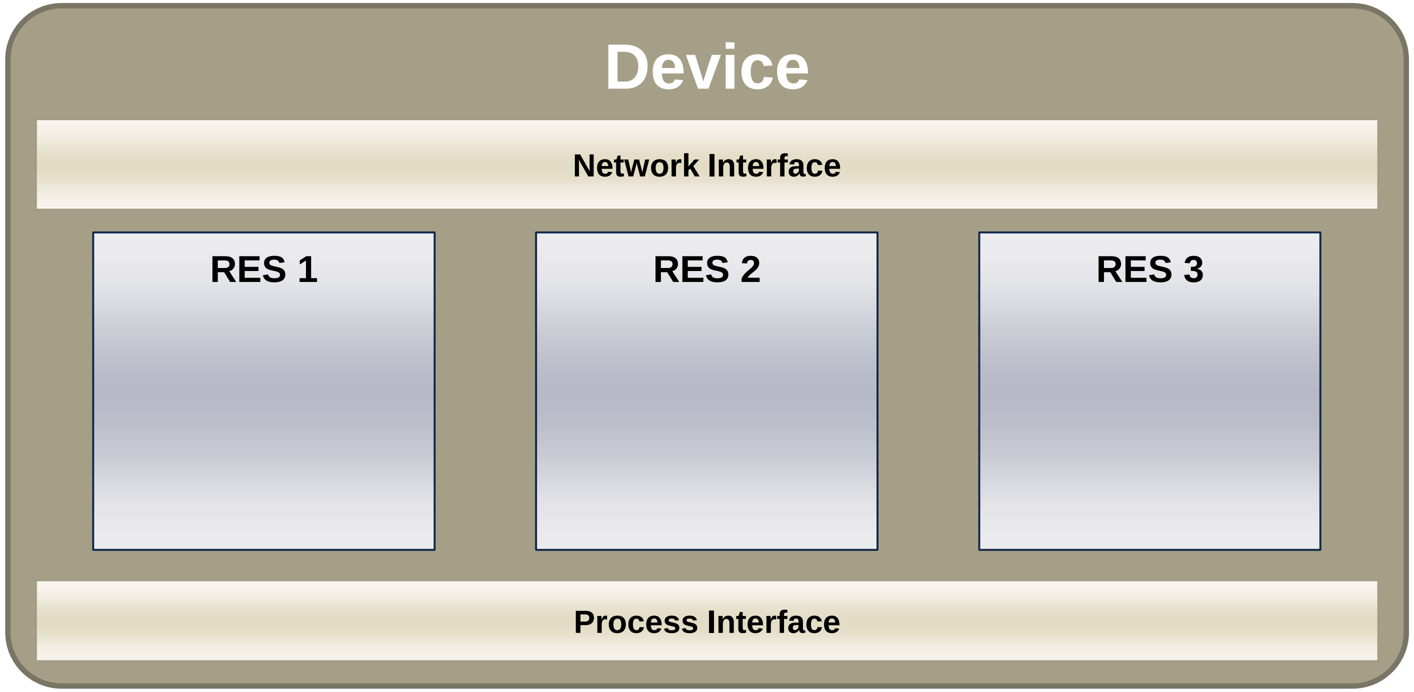
- System Model
  - Devices
  - Process/Machine
  - Communication Infrastructure (Segments & Links)



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

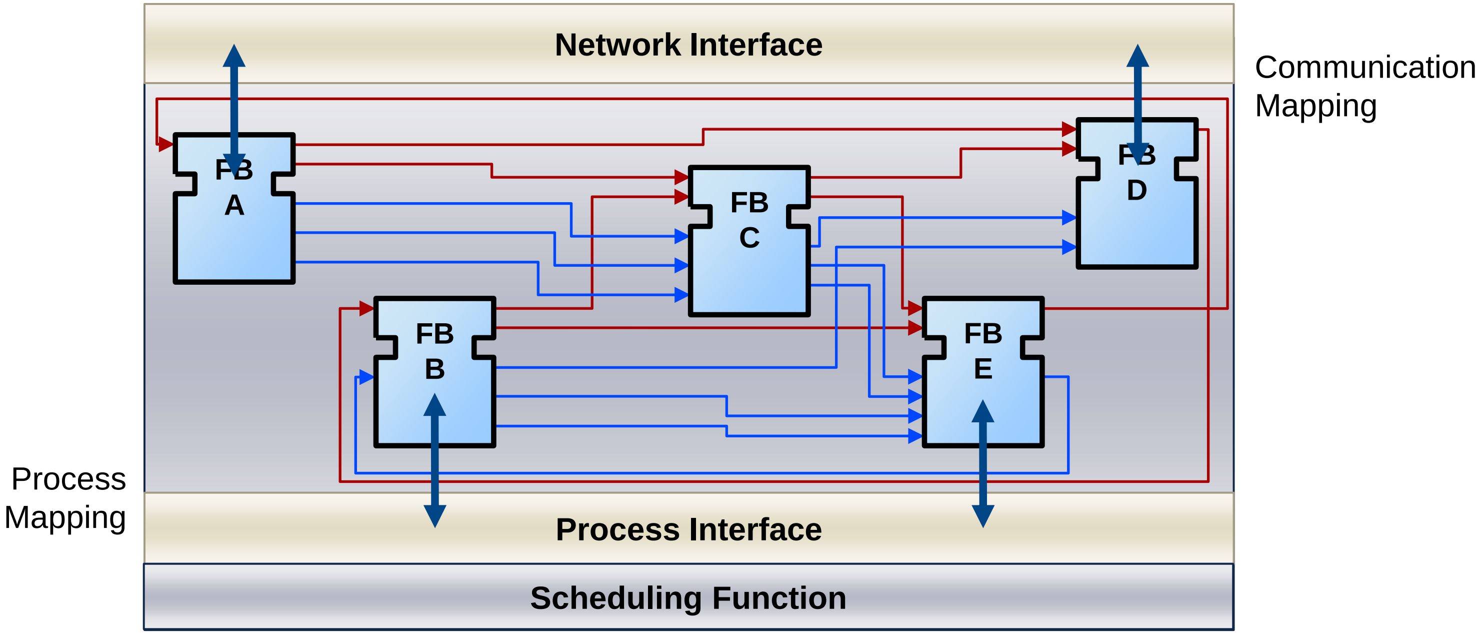
- Device Model
  - Device = container for Resources
  - Device provides Communication & Process Interfaces



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

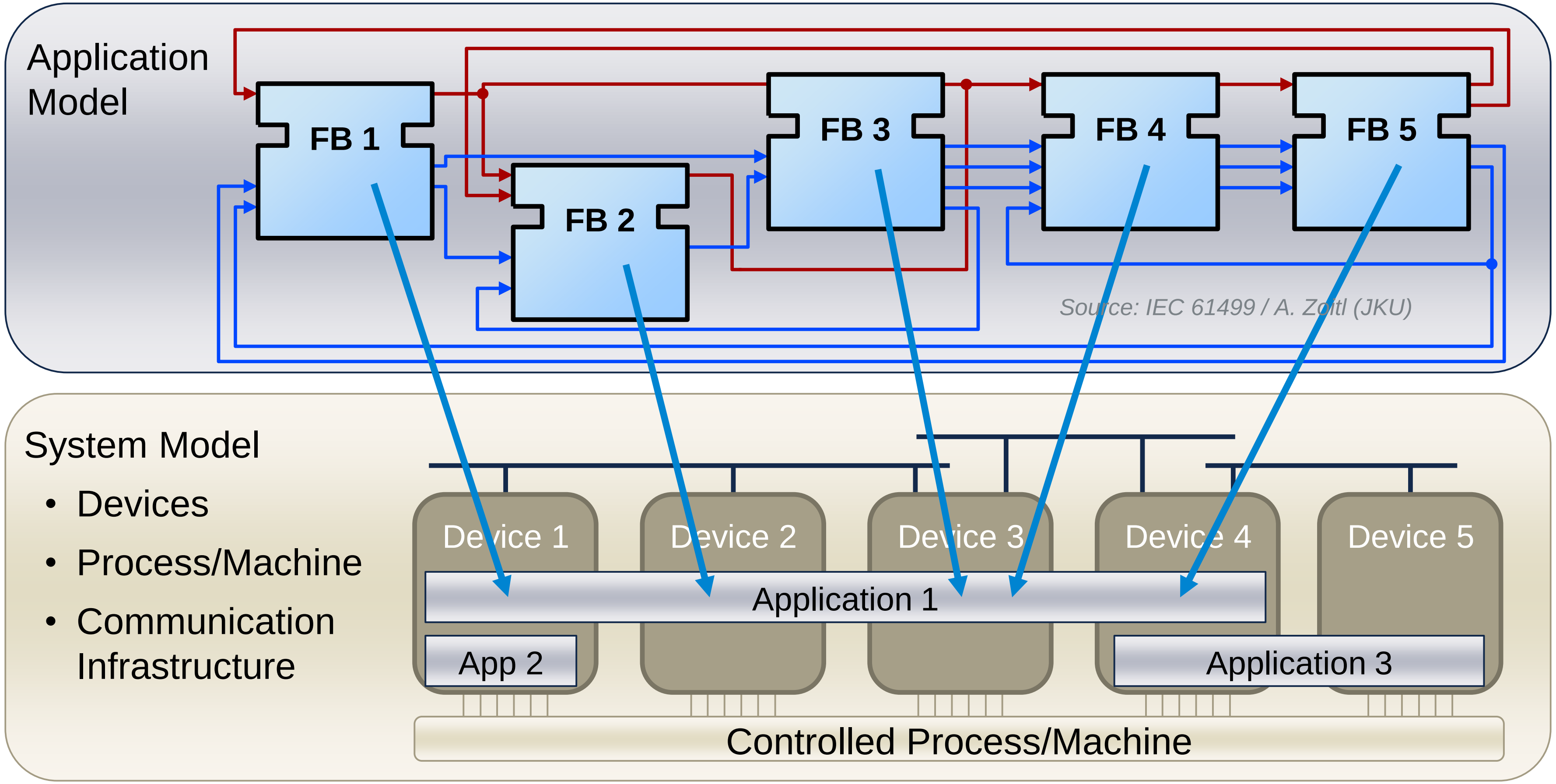
- Resource Model
  - Resource schedules & executes FB algorithms
  - Resource maps Communications & Process I/O functions to SIFB



Source: IEC 61499 / A. Zoitl (JKU)

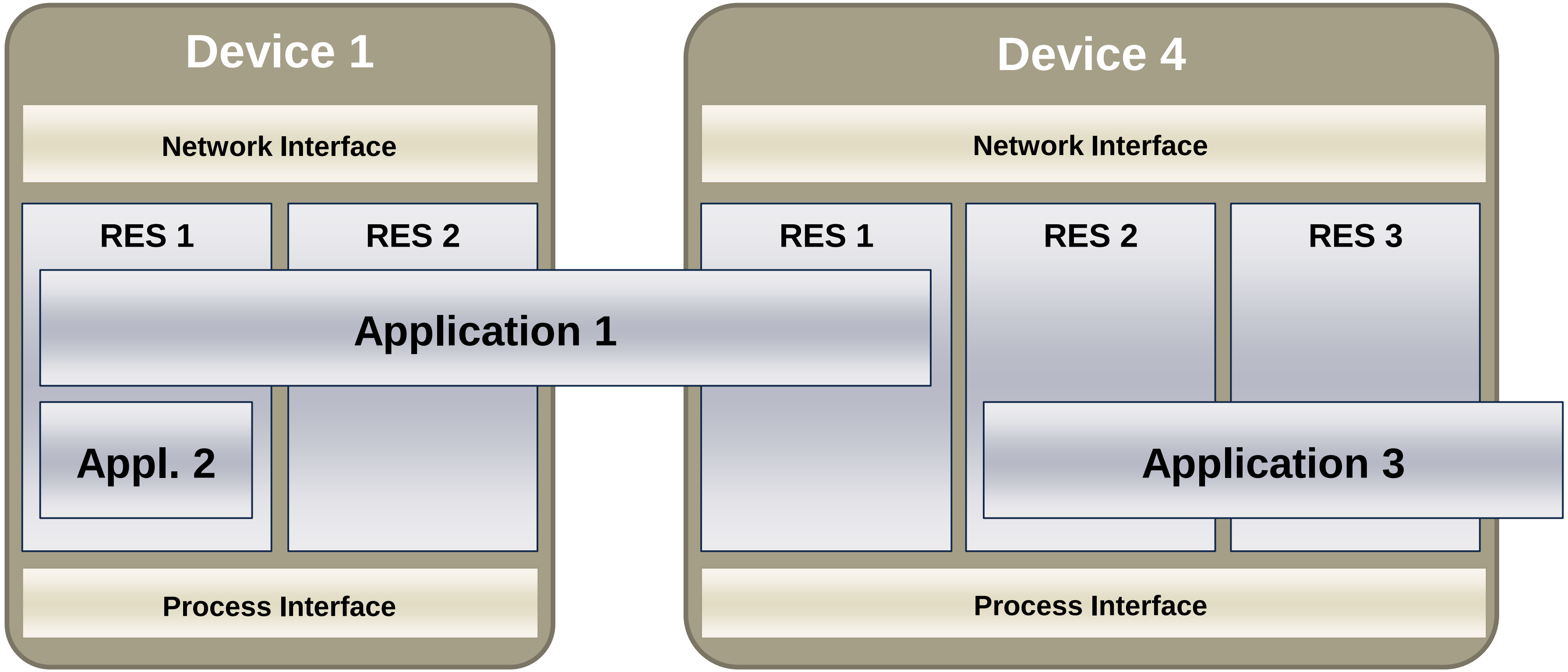
Overview of the IEC 61499 Reference Model

- Distribution Model: distribution of applications



Overview of the IEC 61499 Reference Model

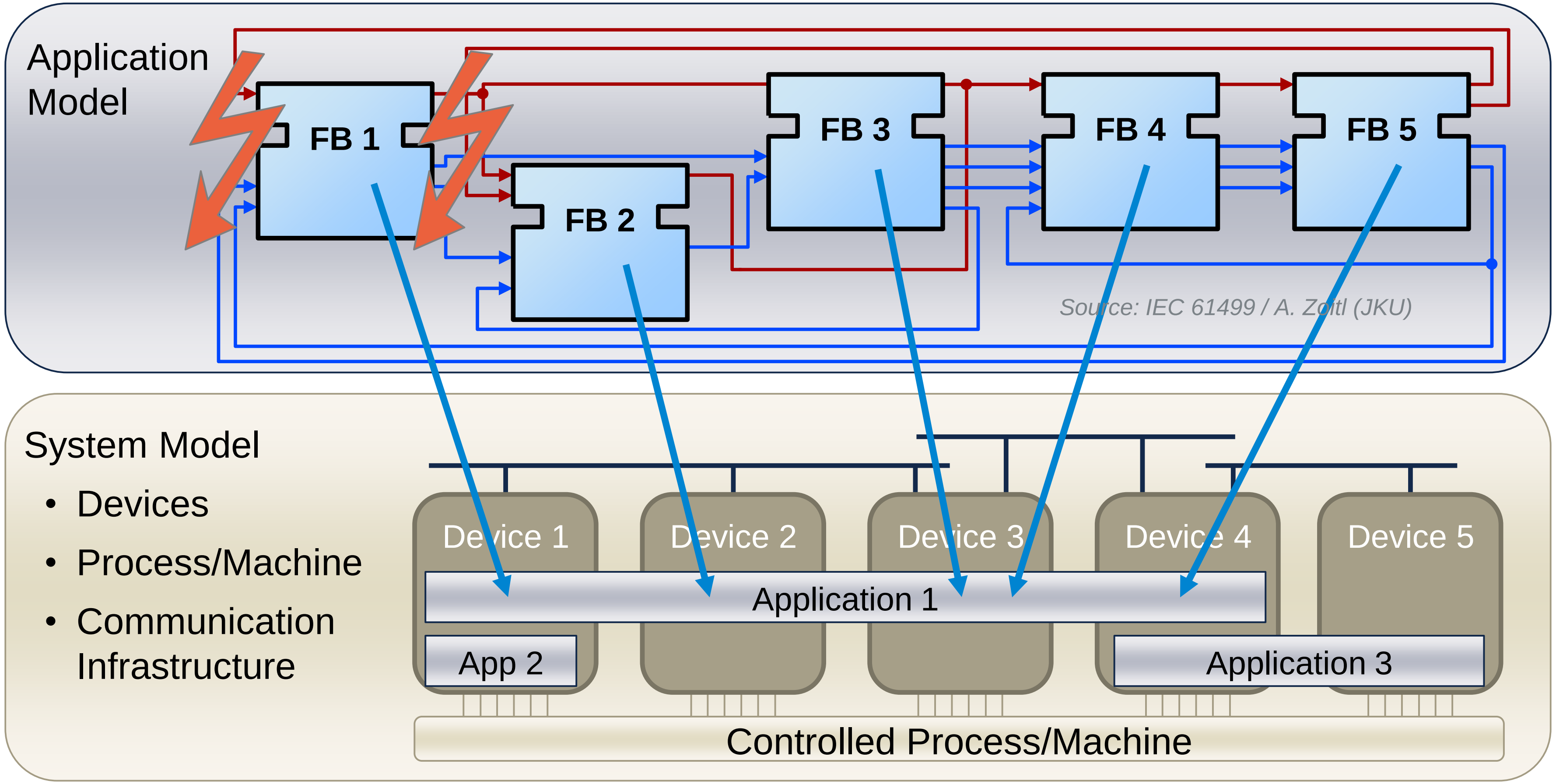
- Distribution Model: distribution to resources



Source: IEC 61499 / A. Zoitl (JKU)

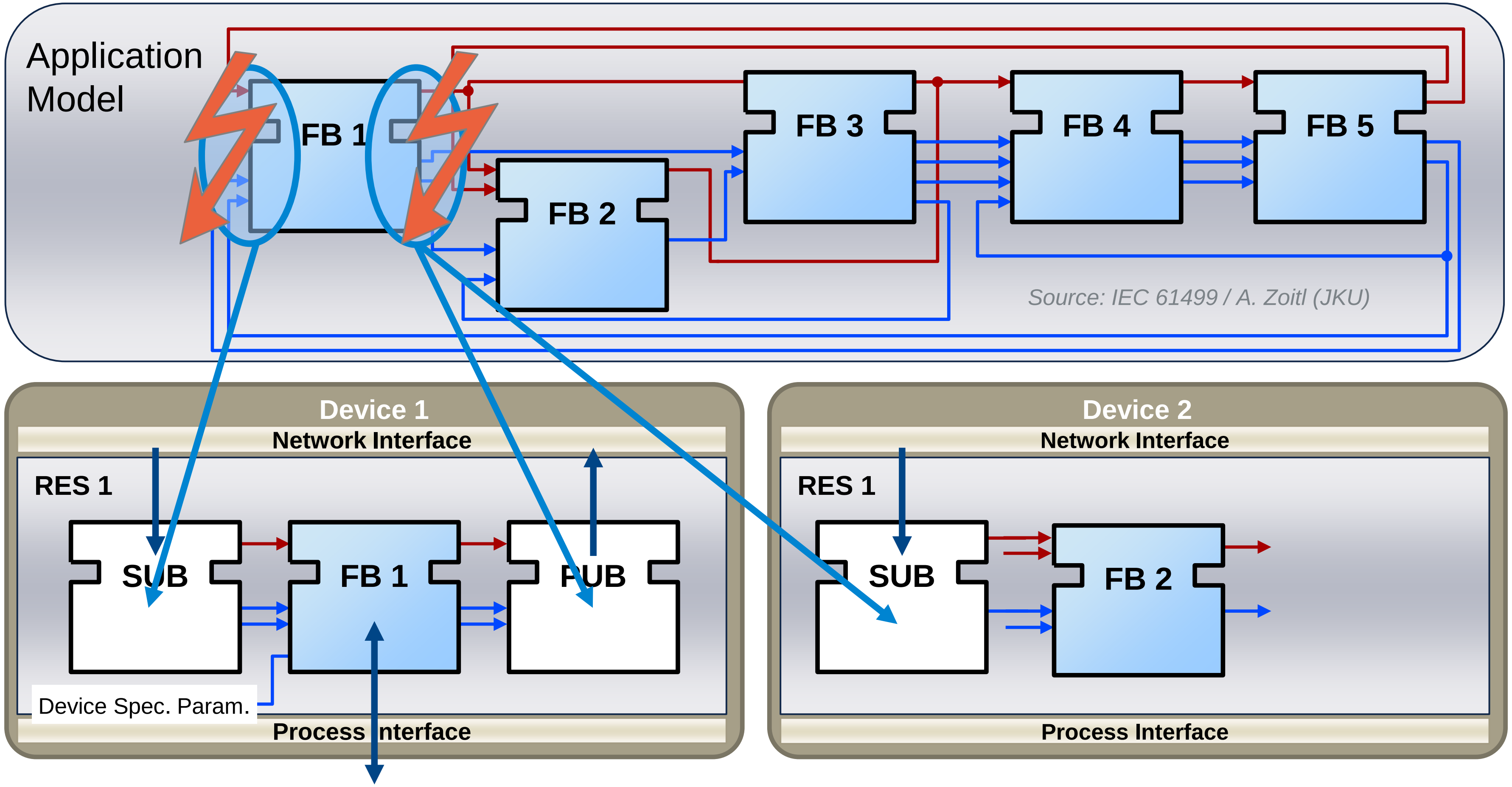
Overview of the IEC 61499 Reference Model

- Distribution Model: device-specific configuration of parameters



Overview of the IEC 61499 Reference Model

- Distribution Model: device-specific configuration of parameters

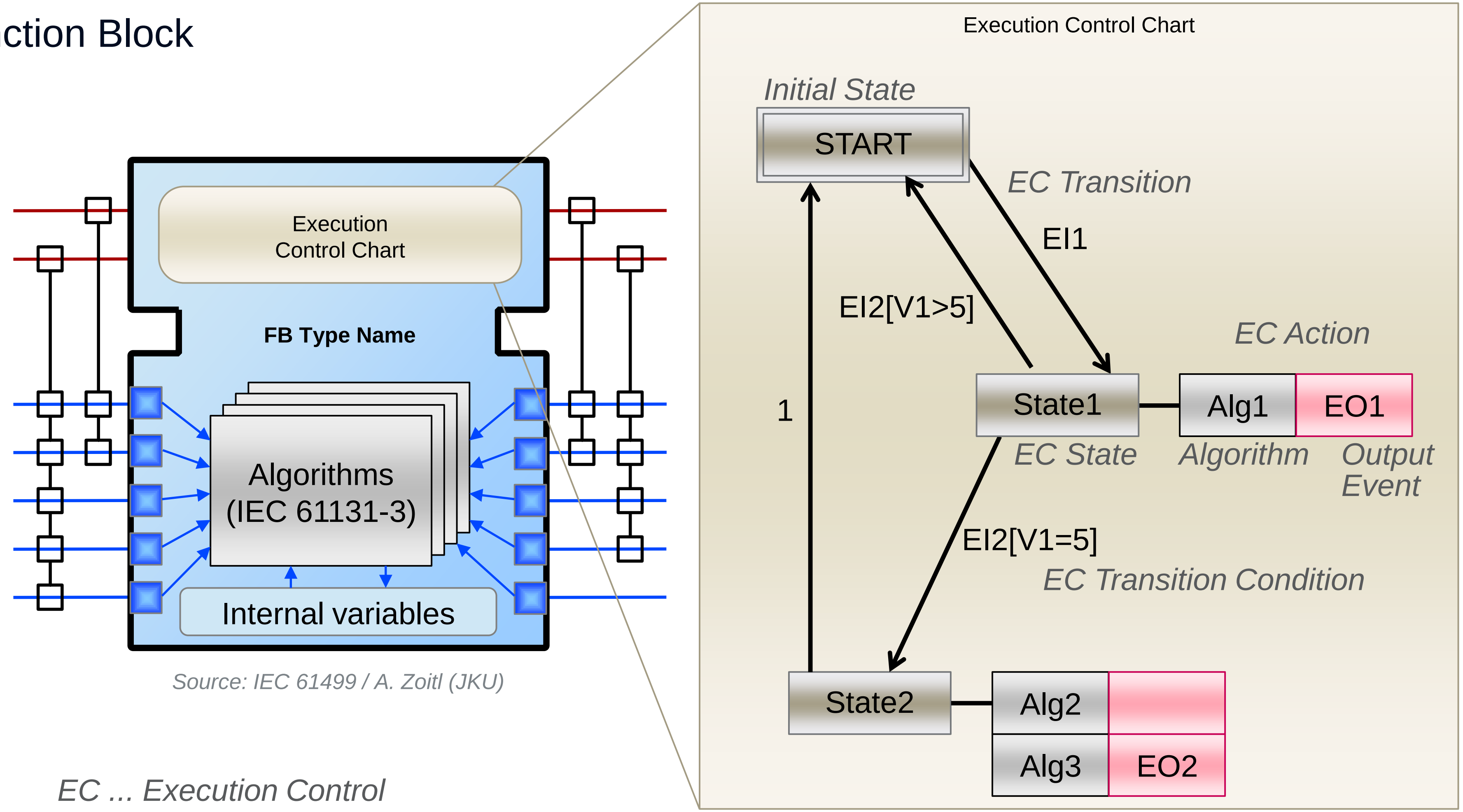


Overview of the IEC 61499 Reference Model

- Five different FB types
  - Basic Function Block (BFB)
  - Composite Function Block (CFB)
  - Service Interface Function Block (SIFB)
  - Adapter Interfaces
  - Subapplications
- Only Event-FBs are defined in the standard for controlling the event flow

Overview of the IEC 61499 Reference Model

- Basic Function Block

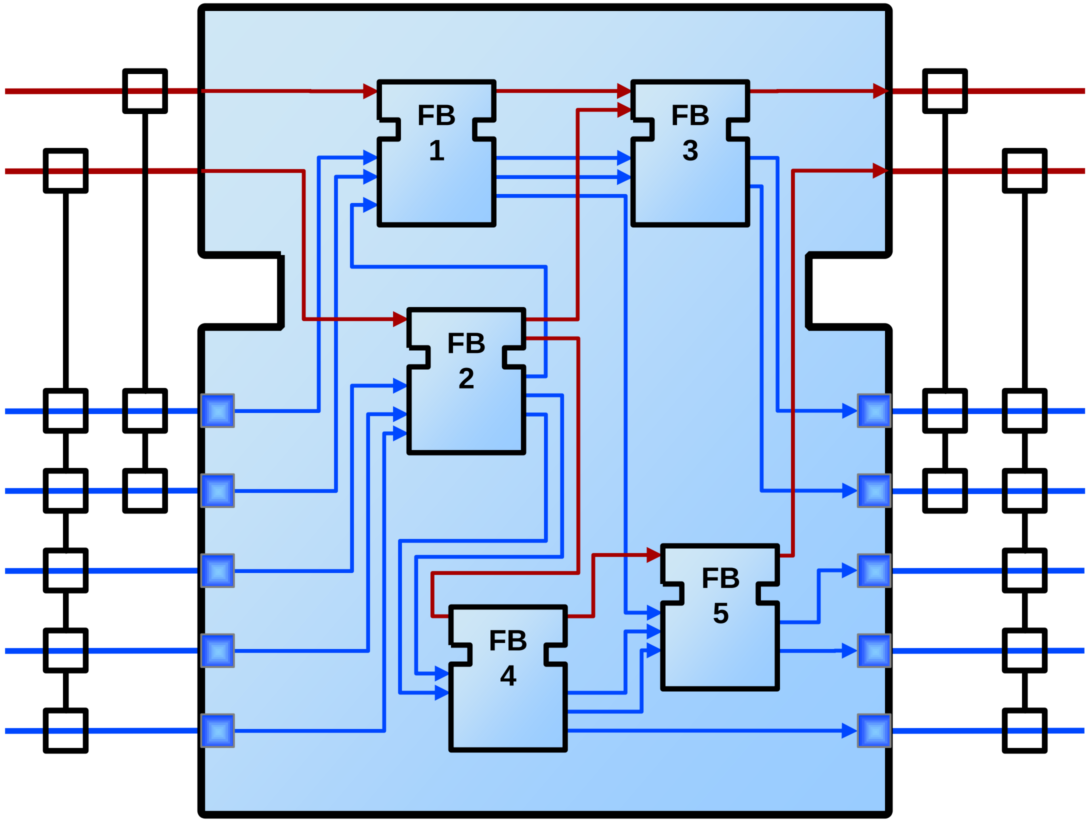


Source: IEC 61499 / A. Zoitl (JKU)

EC ... Execution Control

Overview of the IEC 61499 Reference Model

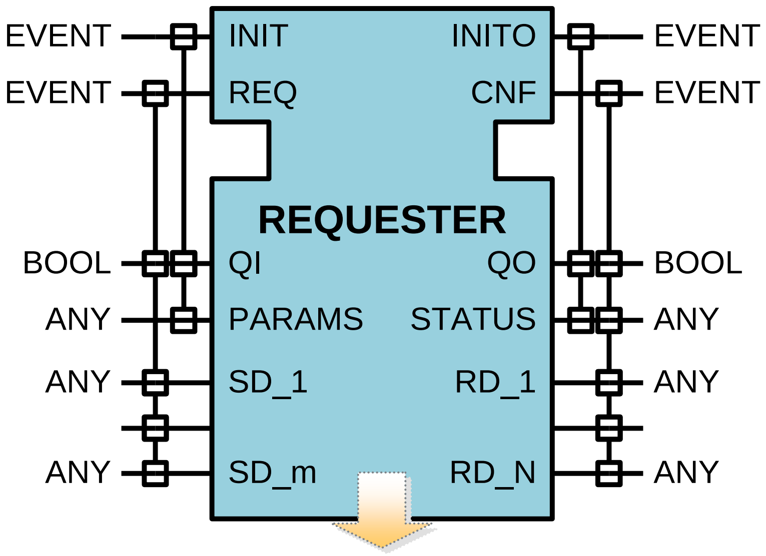
- Composite Function Block
  - Composed out of other BFBs, CFBs, SIFBs and Adapter Interfaces
  - Not distributable



Source: IEC 61499 / A. Zoitl (JKU)

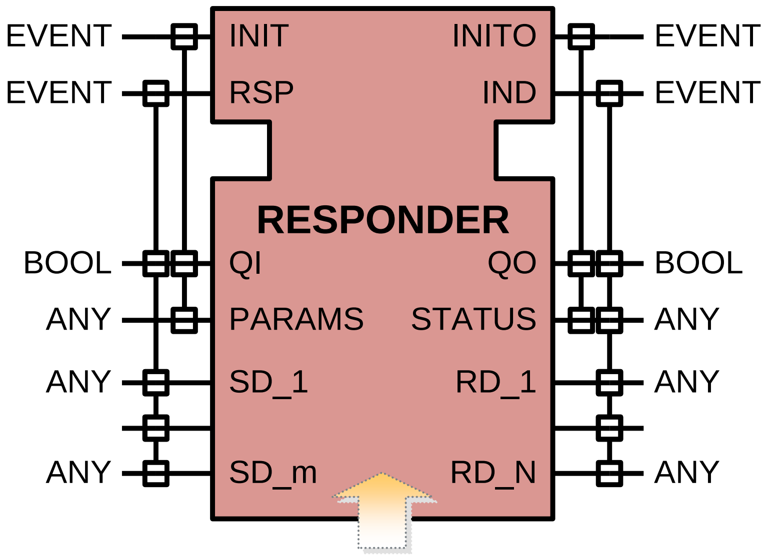
Overview of the IEC 61499 Reference Model

- Service Interface Function Block
  - Access to system specific functionality, e.g., I/Os, HMI, communication (protocol agnostic)
  - Service sequences allow describing the dynamic interface behavior



Application triggered

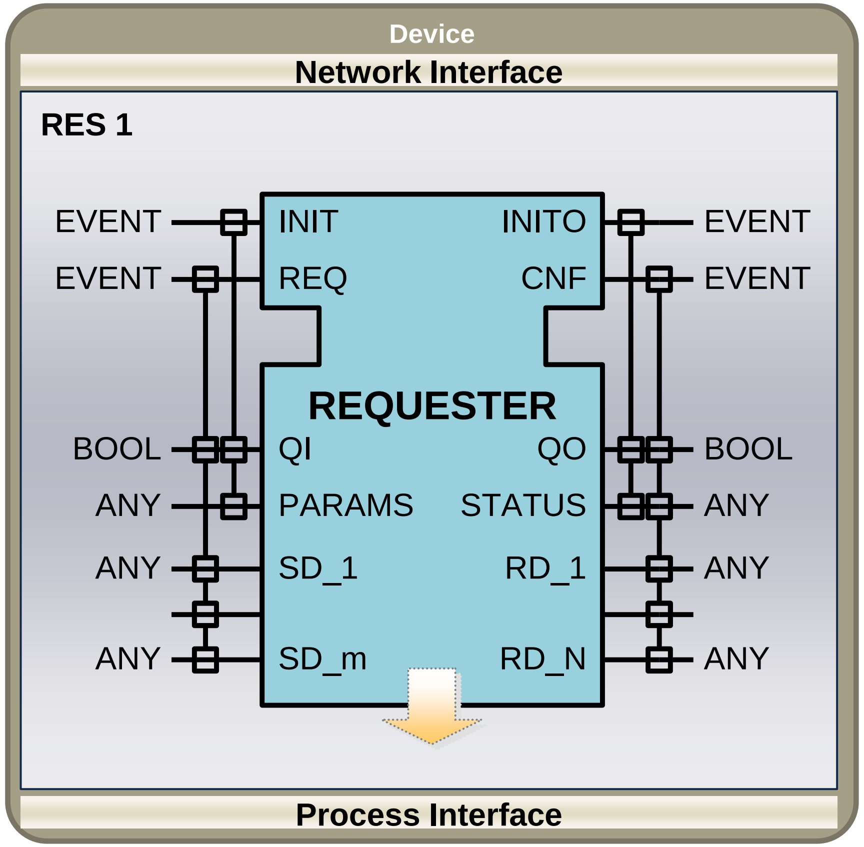
Source: IEC 61499 / A. Zoitl (JKU)

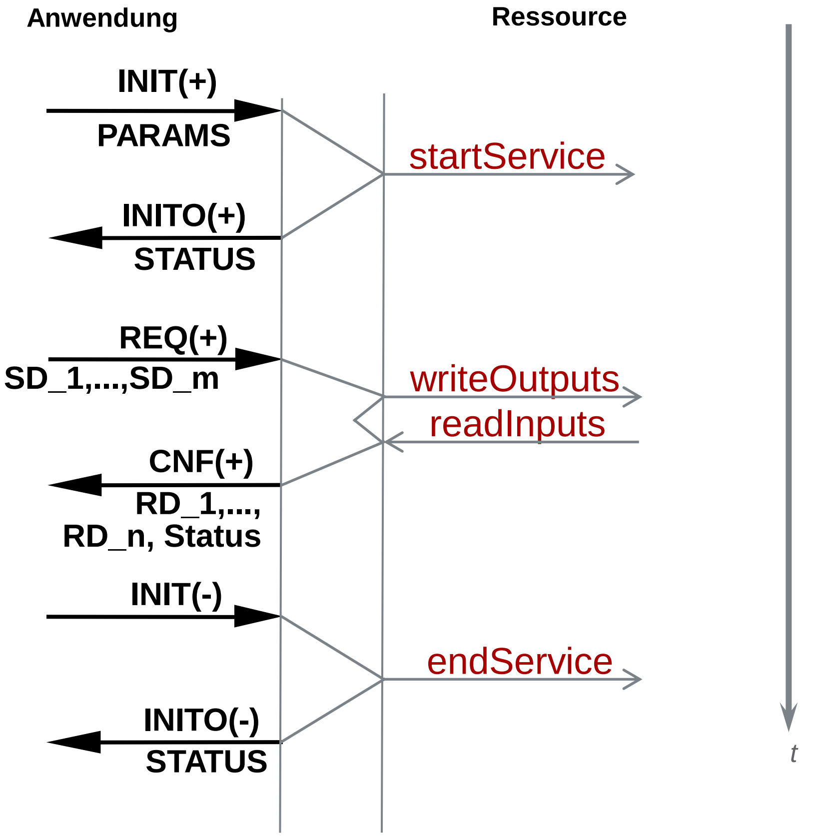


Resource/service triggered

Overview of the IEC 61499 Reference Model

- Service Interface Function Block: Requester (application triggered)

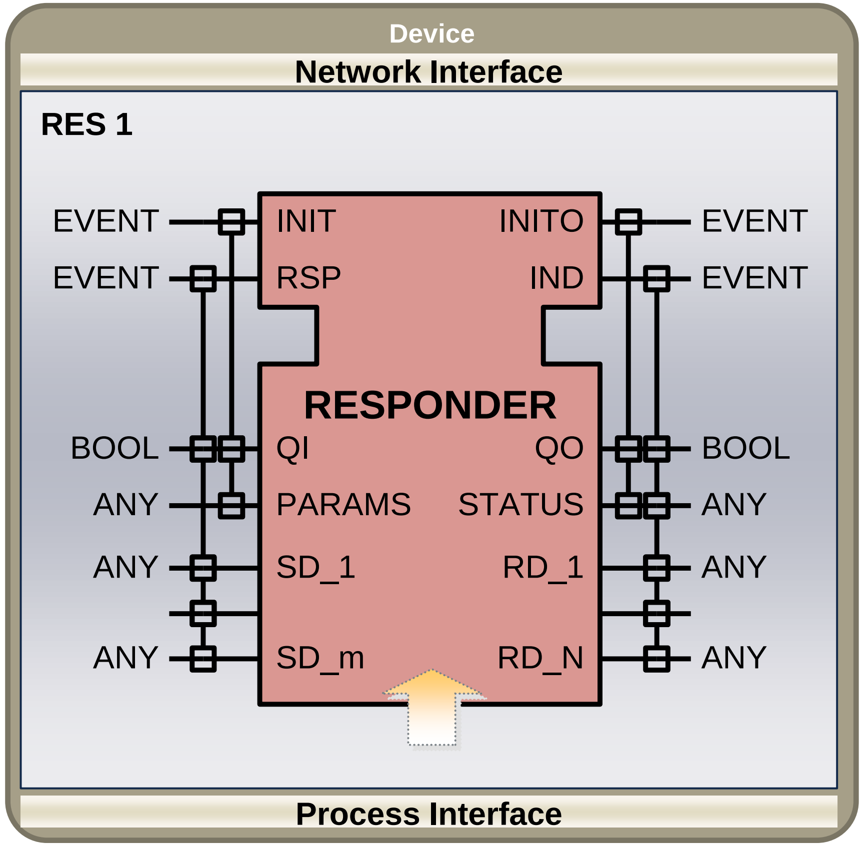


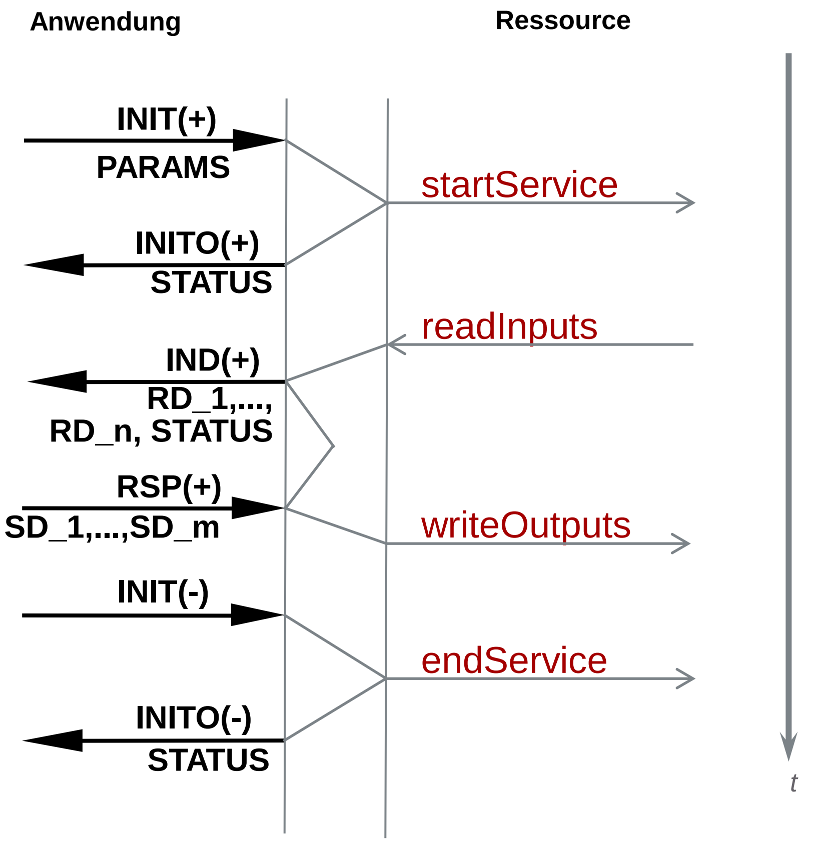


Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

- Service Interface Function Block: Responder (resource/service triggered)



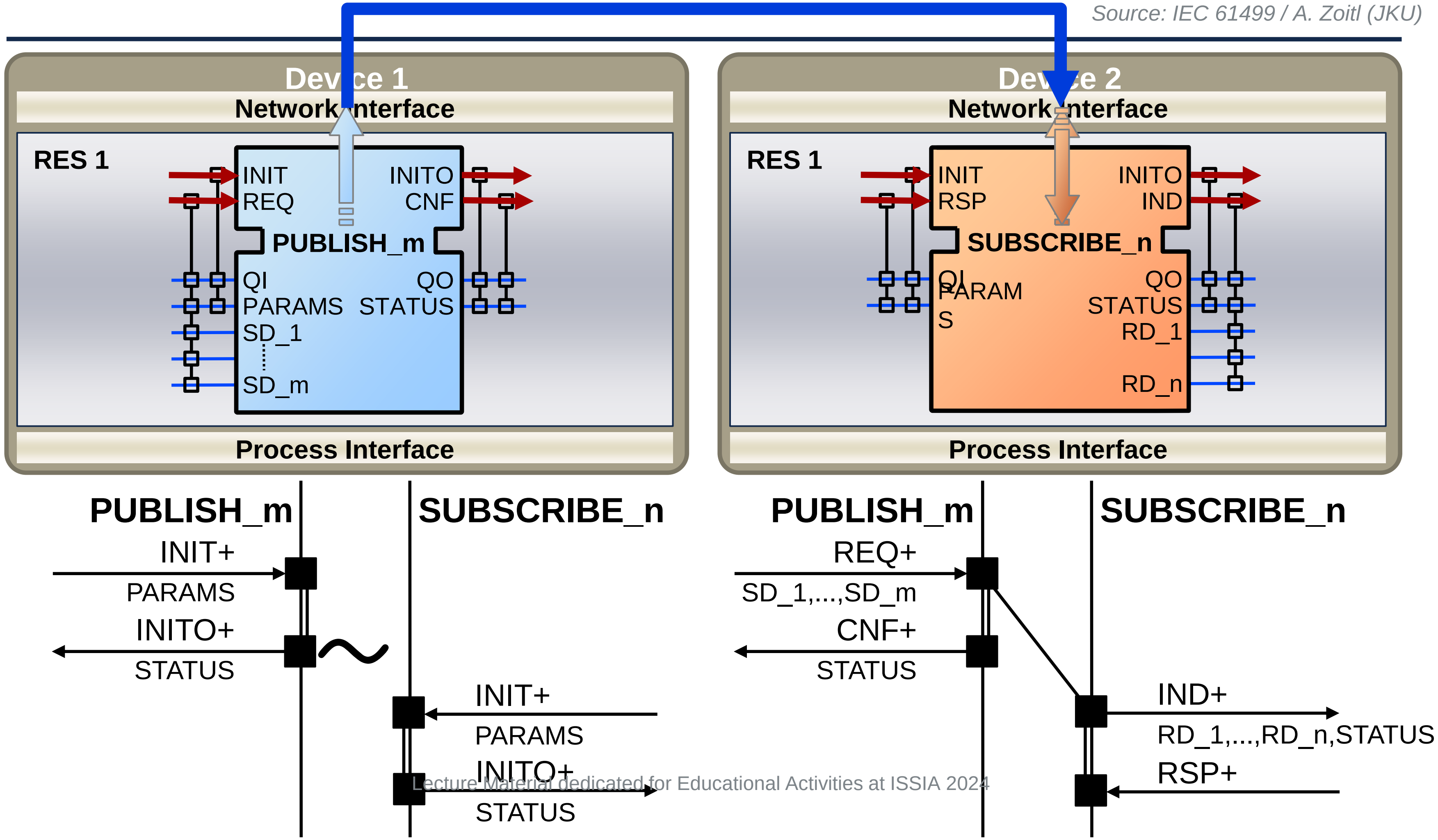


Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

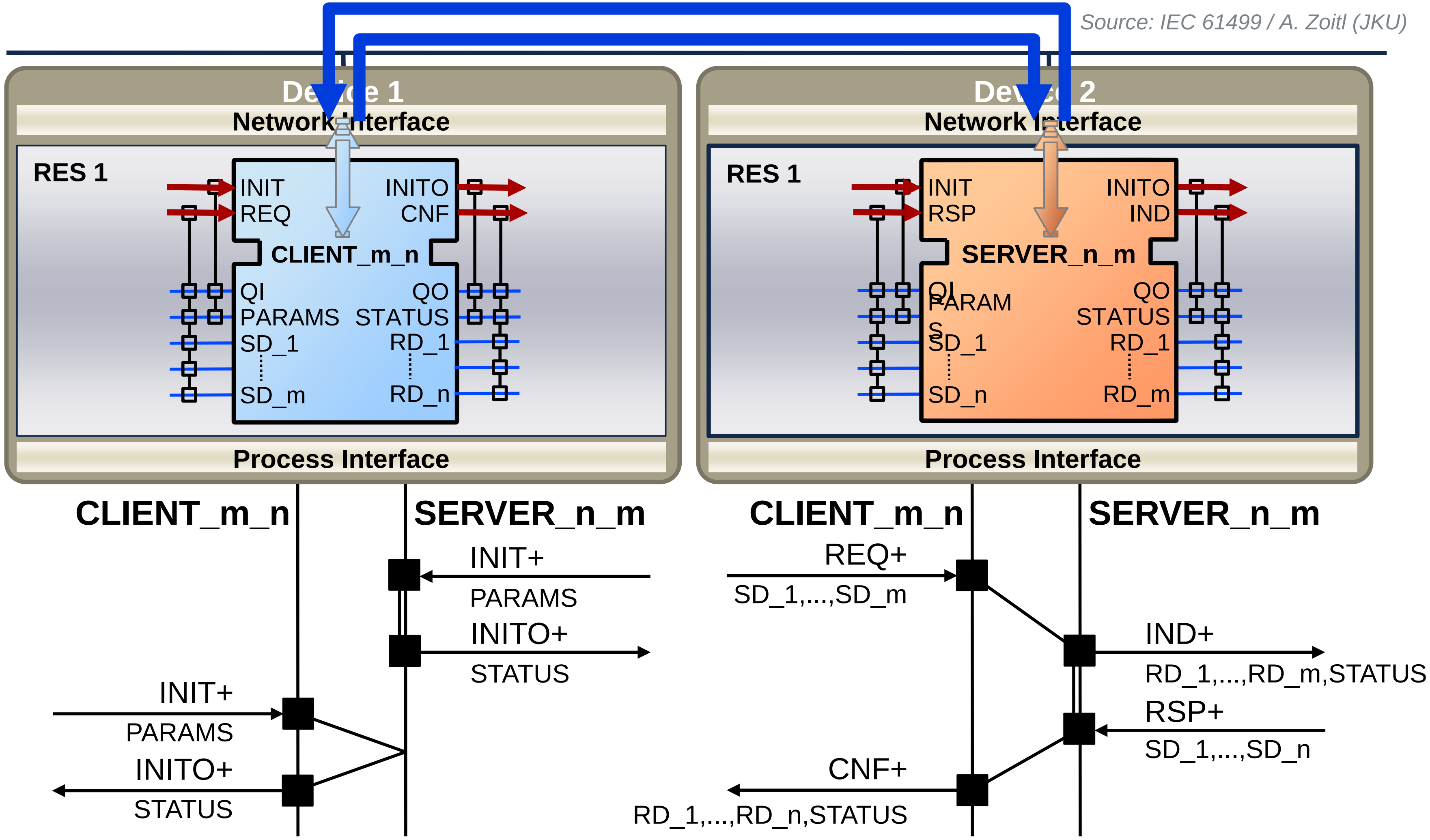
- Service Interface Function Block: Publish/Subscribe Model (uni-directional)

Source: IEC 61499 / A. Zoitl (JKU)



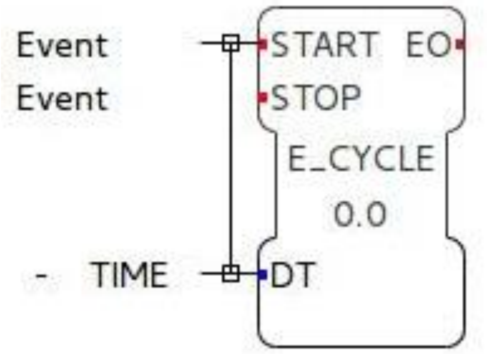
Overview of the IEC 61499 Reference Model

- Service Interface Function Block : Client/Server Model (bi-directional)



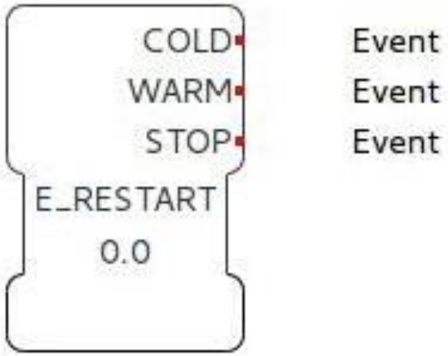
Overview of the IEC 61499 Reference Model

- Event FBs: control of the event flow
  - E_SPLIT/E_MERGE/E_REND - Event split, merge, rendezvous
  - E_PERMIT - Permissive event propagation
  - E_SELECT - 1 of 2 (boolean) event selection
  - E_SWITCH - 1 of 2 (boolean) event demultiplexing
  - E_DELAY - Event delay (timer)
  - E_CYCLE - Periodic event generation



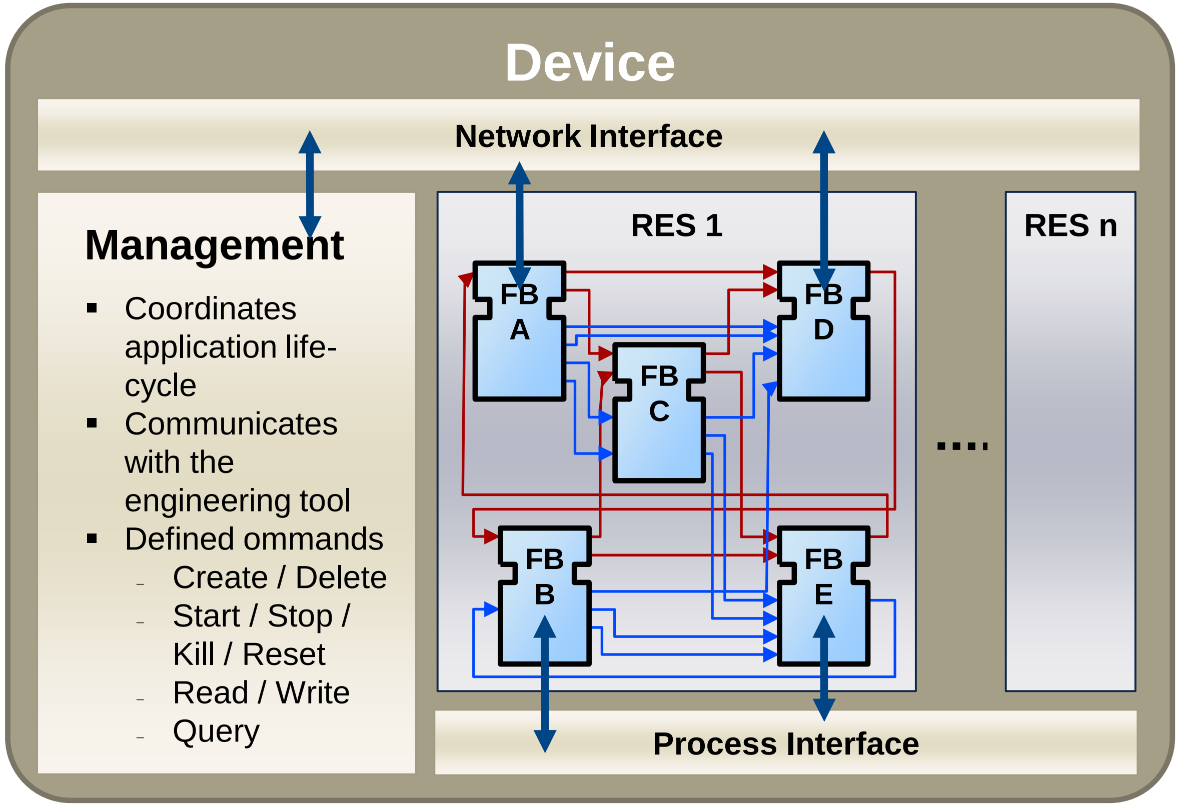
Overview of the IEC 61499 Reference Model

- Event FBs: control of the event flow
  - E_RESTART - Generation of COLD/WARM restart, STOP events
  - E_TRAIN/E_TABLE/E_N_TABLE - Finite trains of events
  - E_SR/E_RS/E_D_FF - Event-driven bistables
  - E_R_TRIG/E_F_TRIG - Event-driven rising/falling edge detection
  - E_SR/E_RS/E_D_FF - Event-driven bistables
  - E_CTU - Event-driven up-counter



Overview of the IEC 61499 Reference Model

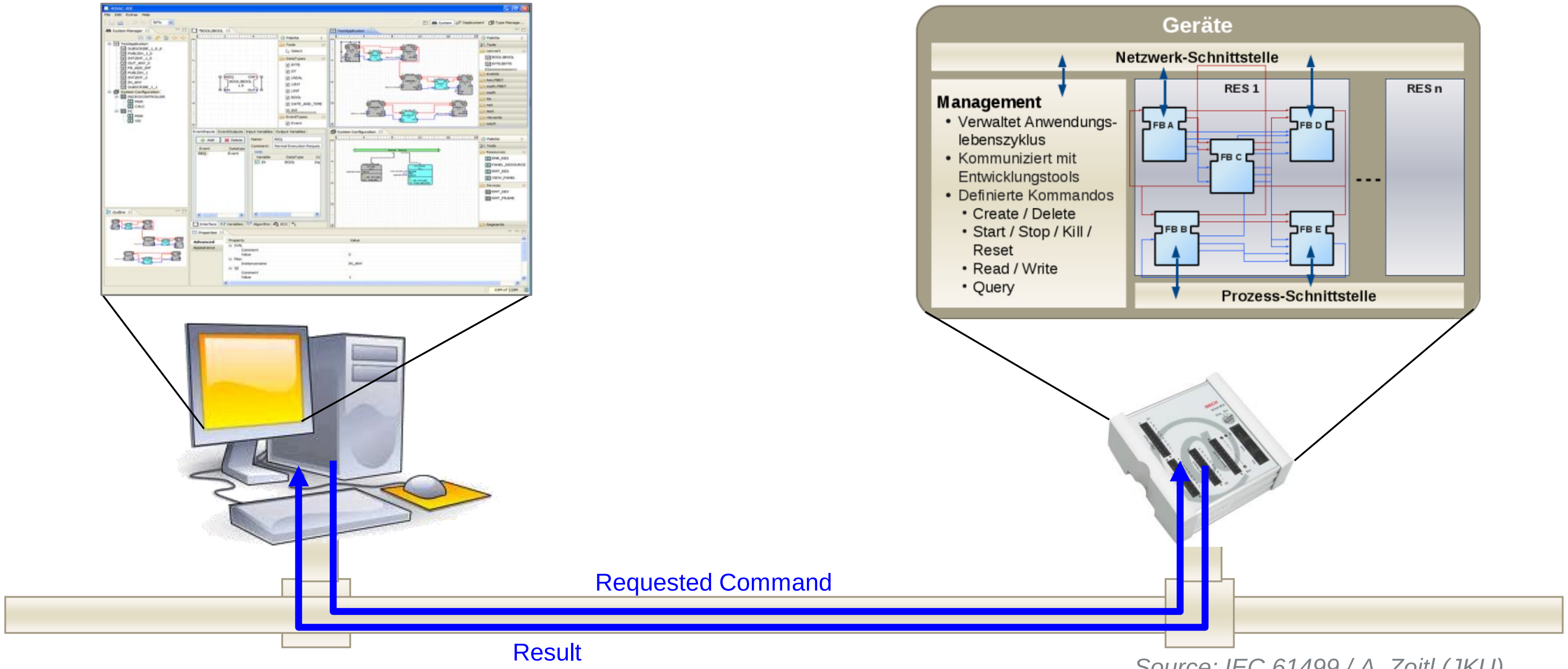
- Device Management Model
  - Query of FBs / Devices / Resources / Connections
  - Creation / deletion of FBs
  - Creation / deletion of connections (event / data)
  - Start / Stop / Kill / Reset of FBs



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

- Device Management Model
  - Software Tools vs. Runtime Device
  - Communication Services vs. Management Services



Source: IEC 61499 / A. Zoitl (JKU)

Overview of the IEC 61499 Reference Model

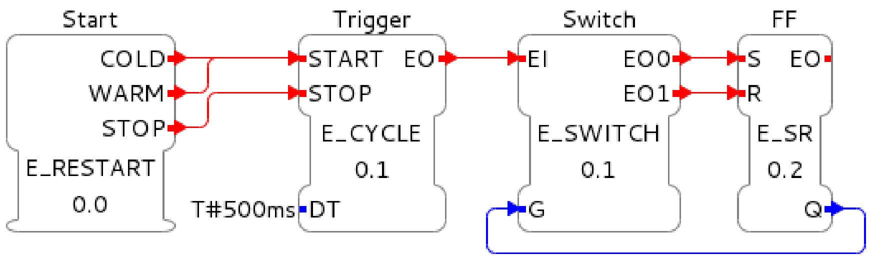
- Device Management Model: XML commands

```
<Request ID="1" Action="CREATE" >
 <FB Name="START" Type="E_RESTART" />
</Request>

<Request ID="2" Action="CREATE" >
 <FB Name="Trigger" Type="E_Cycle" />
</Request>
                    ⋮
<Request ID="5" Action="WRITE" >
 <Connection Source="T#500ms" Destination="Trigger.DT" />
</Request>

<Request ID="6" Action="CREATE" >
 <Connection Source="START.COLD" Destination="Trigger.START" />
</Request>
                    ⋮
<Request ID="12" Action="CREATE" >
 <Connection Source="FF.Q"
  Destination="Switch.G" />
</Request>

<Request ID="13" Action="START" >
</Request>
```



Responses

- Positive:

  `<Response ID="1" />`

- Negative:

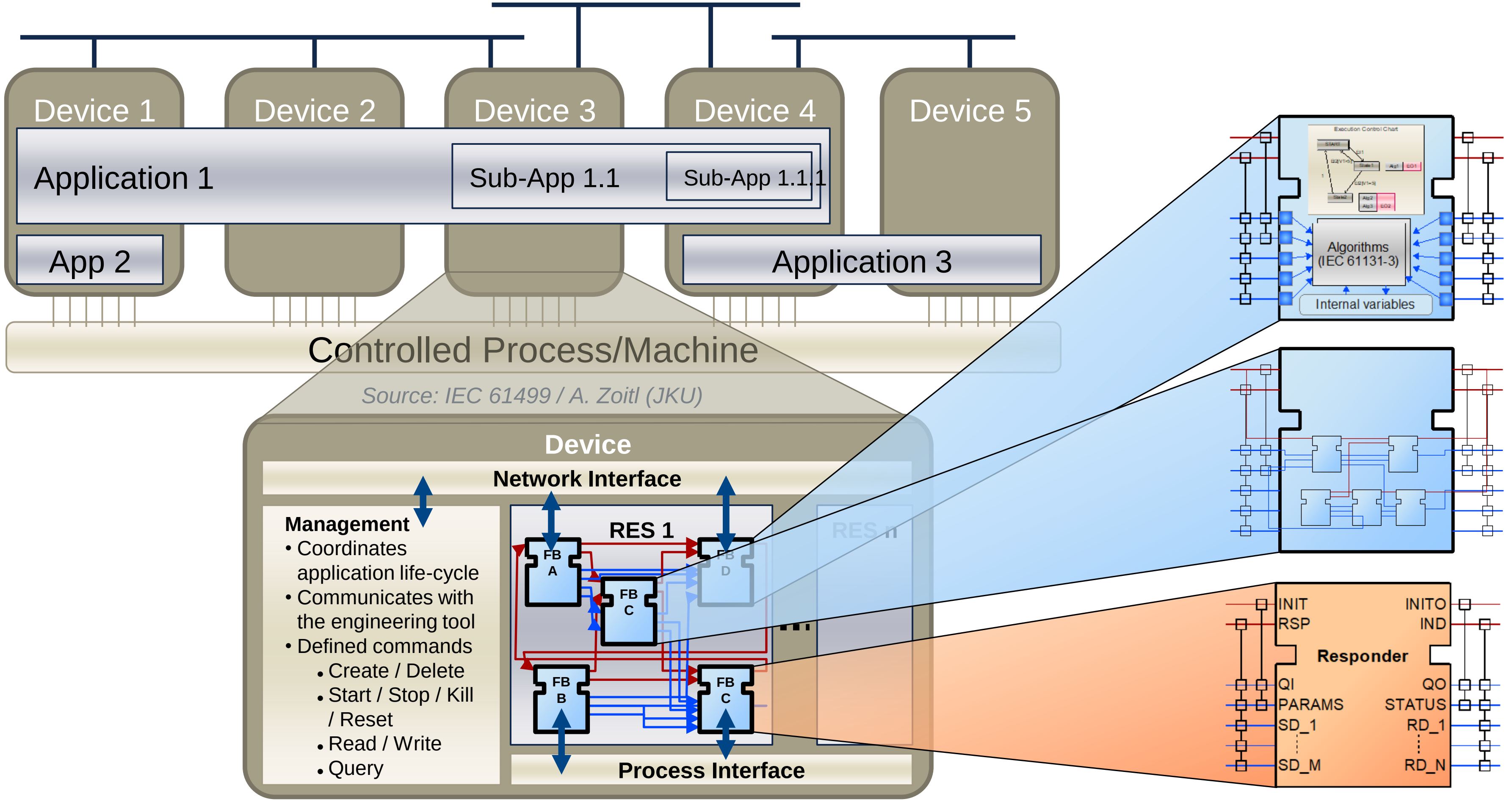
  `<Response ID="1" Reason=”xxx” />`

Overview of the IEC 61499 Reference Model

- Device Management Model: reconfiguration needs
  - Change the overall functionality of the control program
    (e.g., change the sequence of a machine)
  - Add additional functionality to the control program by adding additional software components or rewire existing ones
  - Replace a software component
    (e.g., bug fix in a control algorithm)
  - Change a parameter of a software component
    (e.g., adjust a control algorithm to changed environmental conditions)
  - Move a software component to another control device
    (e.g., breakdown or overload of a control device)
  - Remove a software component
    (e.g., a product is no longer produced)

Overview of the IEC 61499 Reference Model

- Summary: overview of all models



Source: IEC 61499 / A. Zoitl (JKU)

Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

3. Design Process for IEC 61499 Applications

Design Process for IEC 61499 Applications

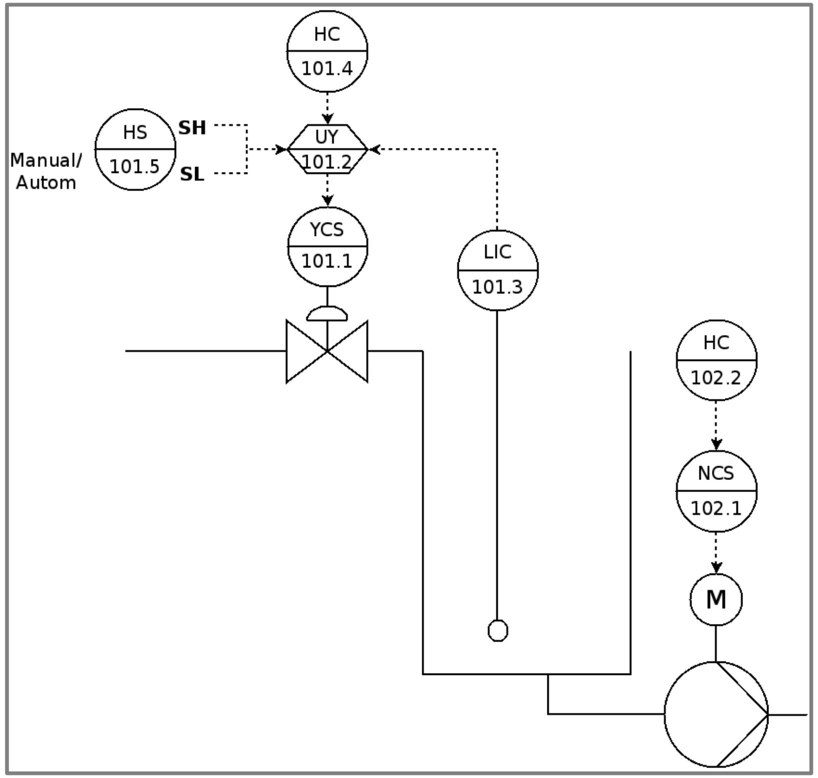
- Application-oriented design / development approach

  Application → System → Distribution → Configuration

  - Model application (application-centered way)
    - Define, develop & test application independent from target devices
    - Utilize existing FBs from library or develop new FBs if needed
  - Define system configuration
    - Define and configure devices and their resources
    - Define network topology
  - Distribute to devices (map FBs of application to the devices & resources)
  - Device specific parameters and adjustments
    - Insert & configure comm. SIFBs for broken event / data connections
    - Define device & system specific parameters (IO port addresses, etc.)

Design Process for IEC 61499 Applications

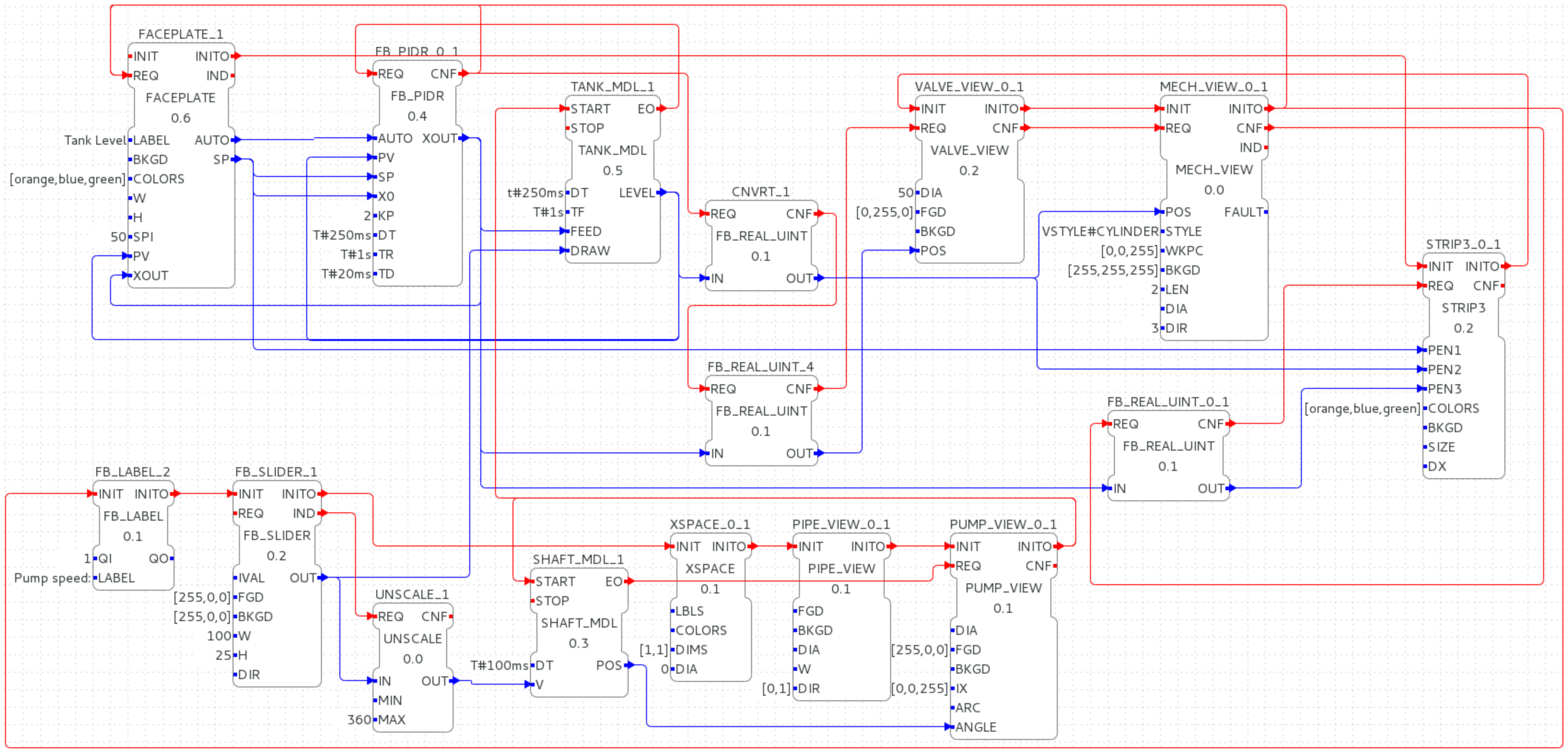
- Example
  - Fill level control of a tank
  - Pump draining independently → disturbance
  - Simulated tank, valve, and pump
  - Simple HMI
    - Set-point
    - Hand / automatic
    - Strip chart



Based on an example from HoloBloc (James Christensen)

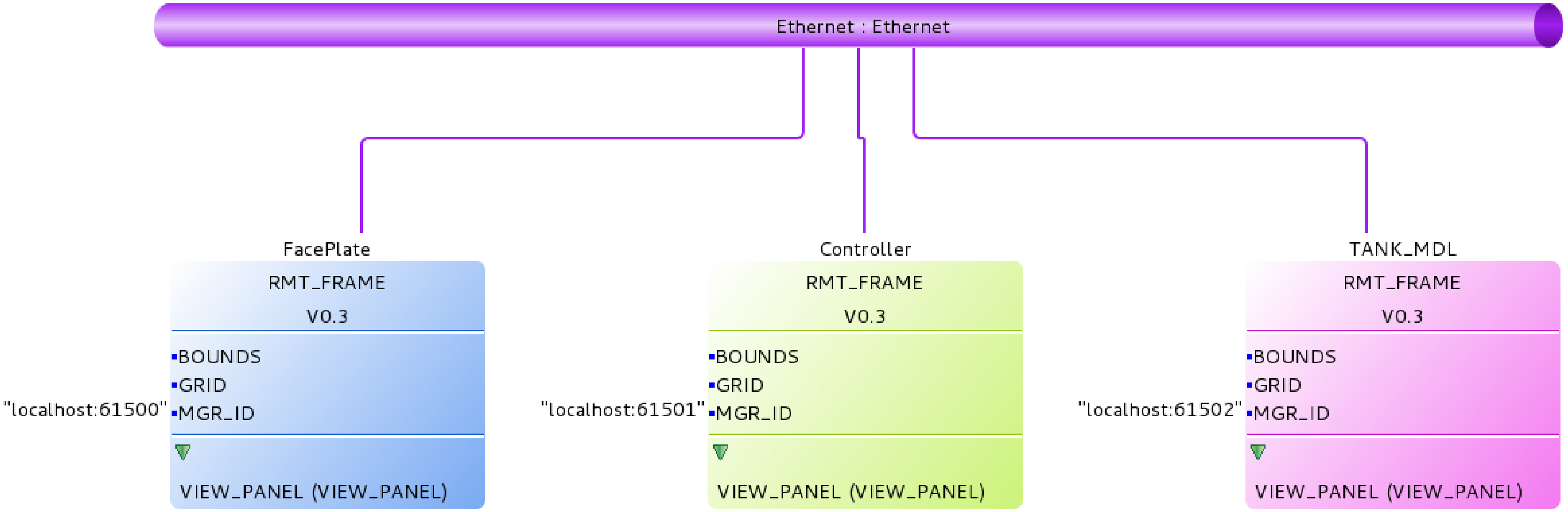
Design Process for IEC 61499 Applications

- Example
  - Model application (application-centered way)



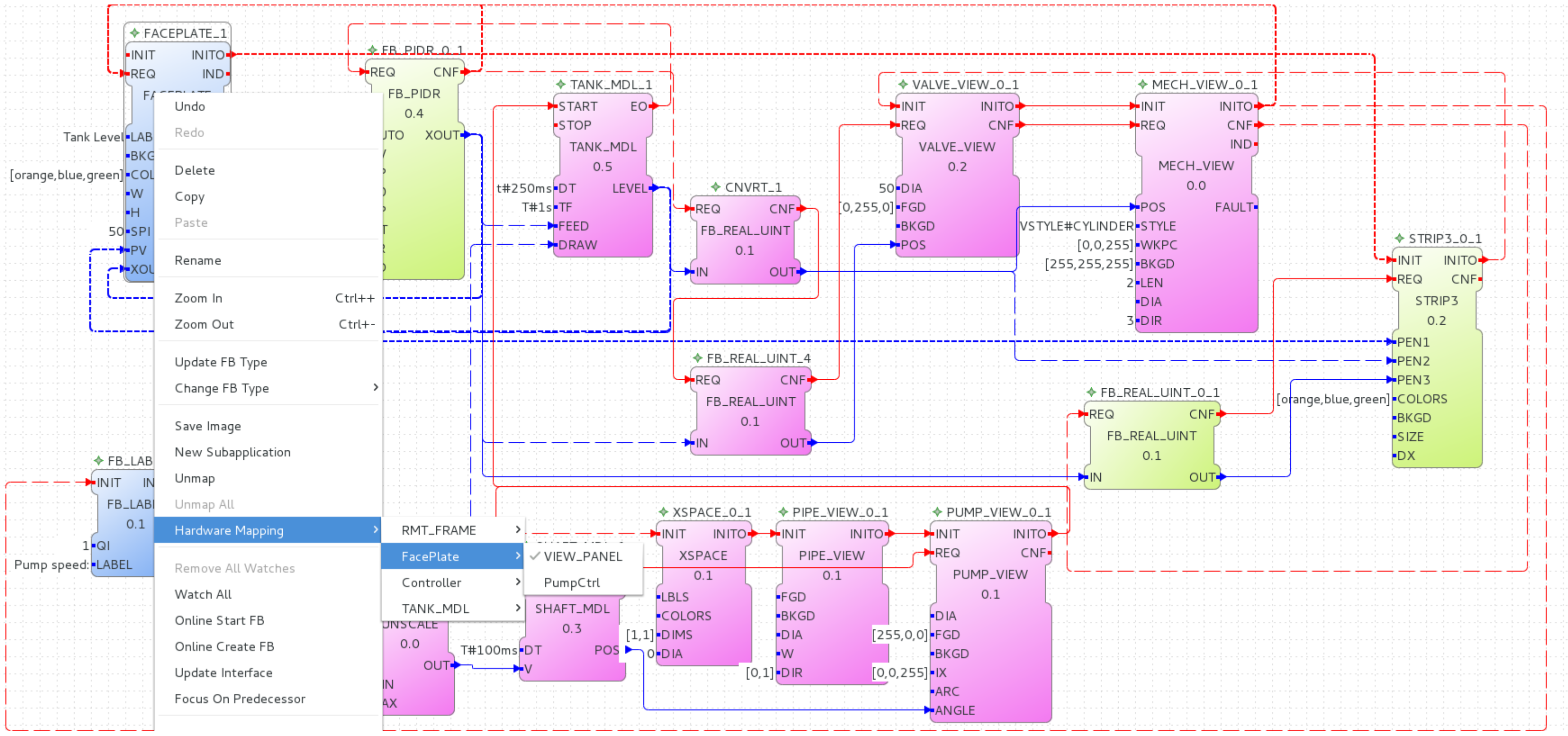
Design Process for IEC 61499 Applications

- Example
  - Define system configuration



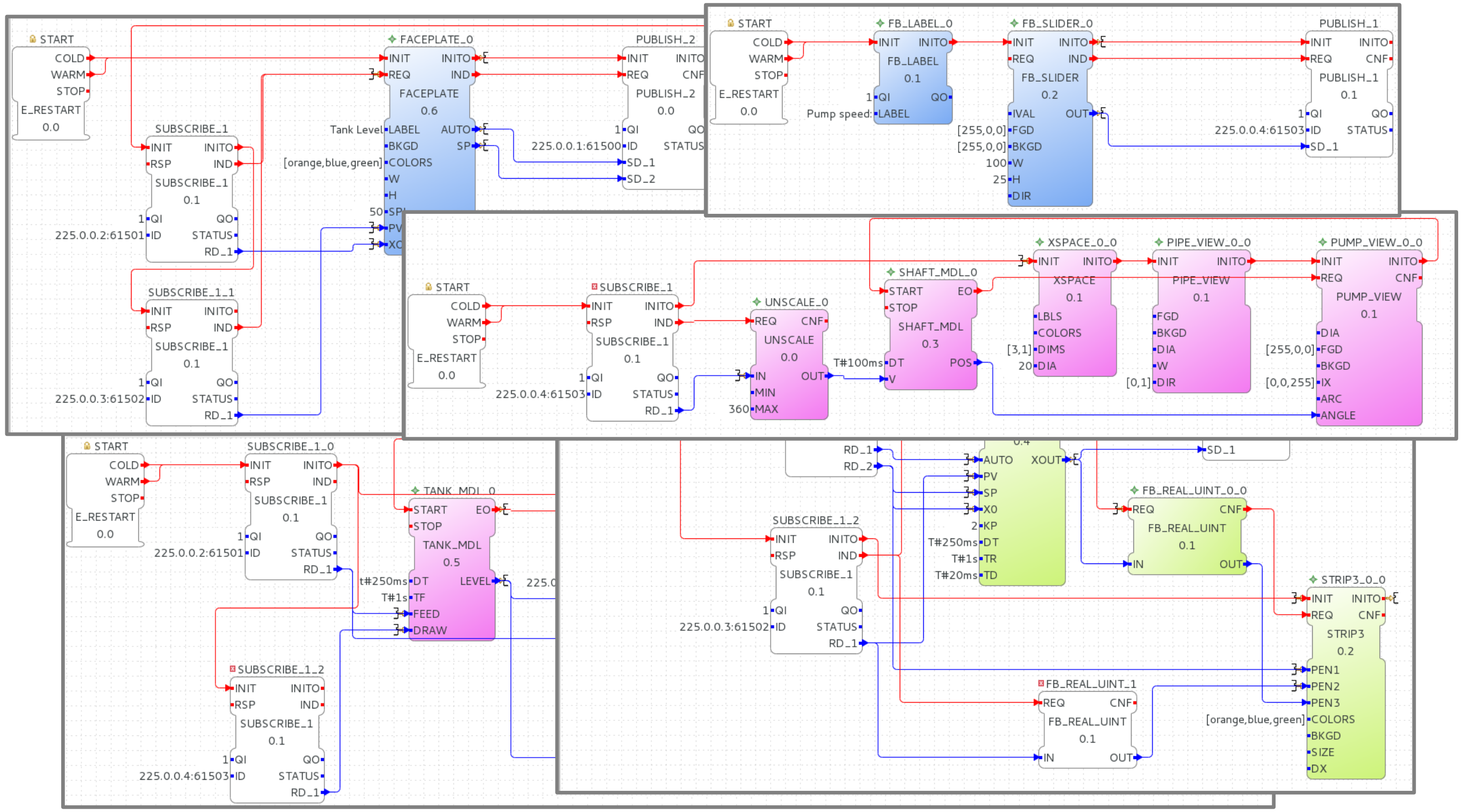
Design Process for IEC 61499 Applications

- Example
  - Distribute to devices



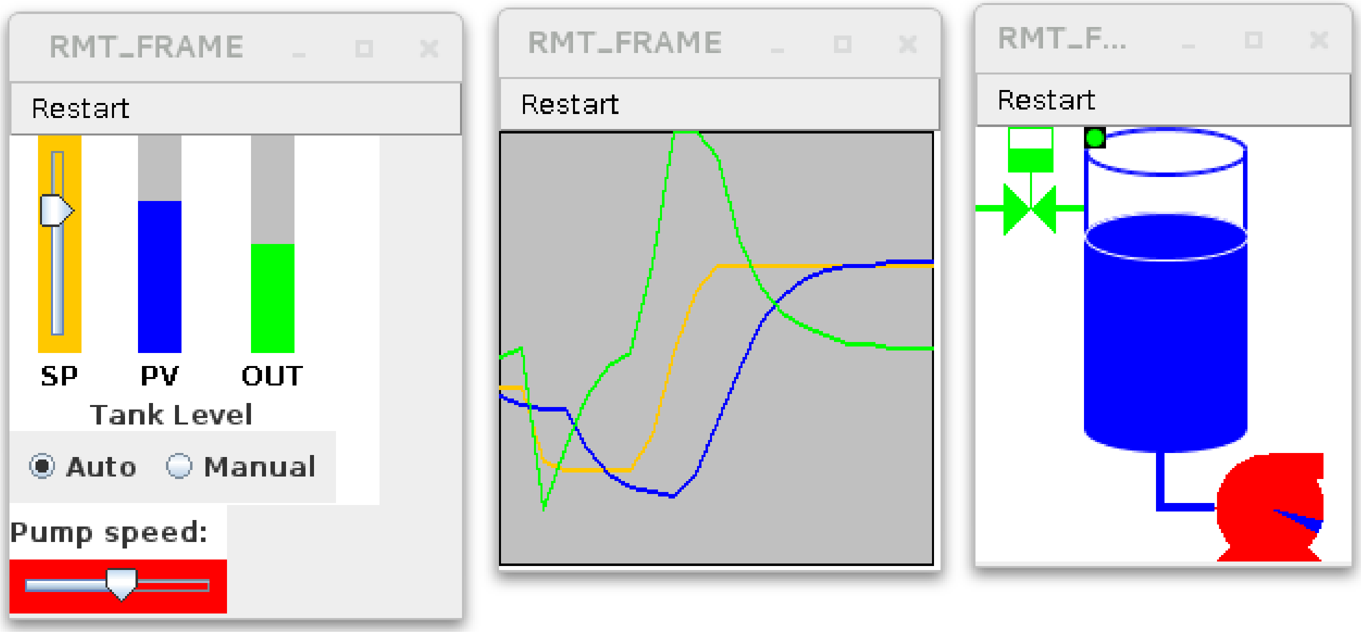
Design Process for IEC 61499 Applications

- Example
  - Device specific parameters and adjustments



Design Process for IEC 61499 Applications

- Example
  - Deployment and execution



Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

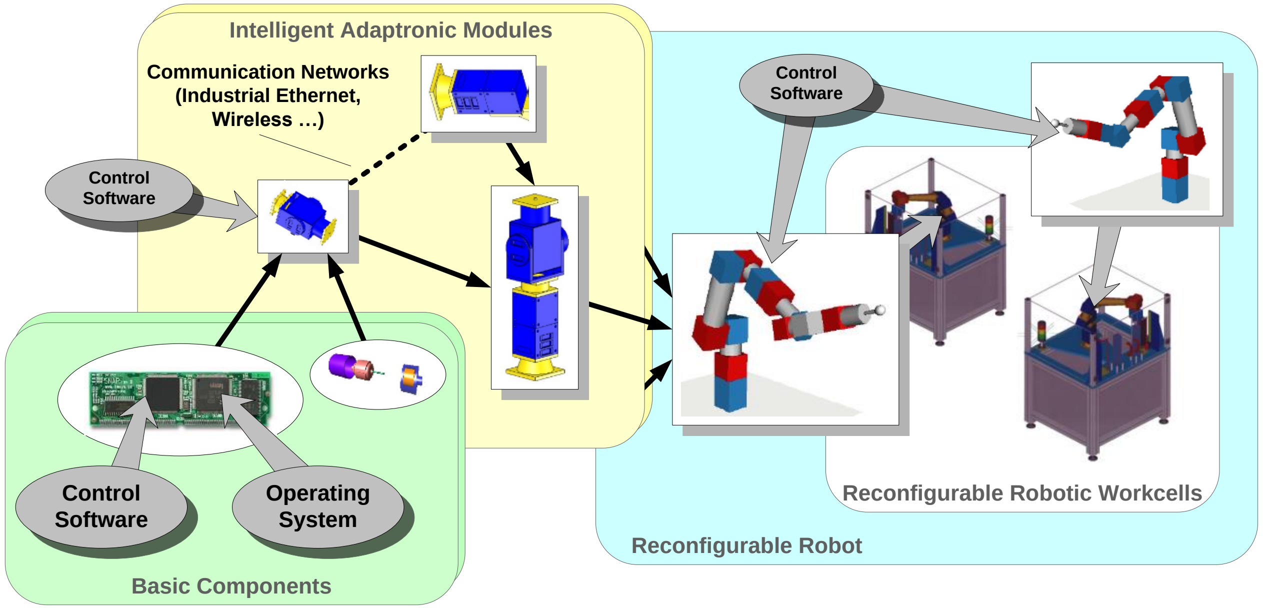
4. Selected Examples

Selected Examples

- Reconfigurable robot arm control
- Three tank control
- Tap-changer control
- Micro grid control
- AIT SmartEST lab automation

Selected Examples

- Reconfigurable robot arm control
  - Standard interfaces (mechanical, electrical)
  - Component databases
  - Assembly system planning tools (simulation)

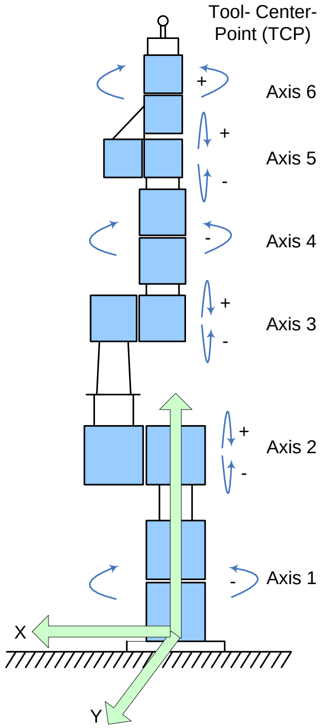


Selected Examples

- Reconfigurable robot arm control

Real

Schema

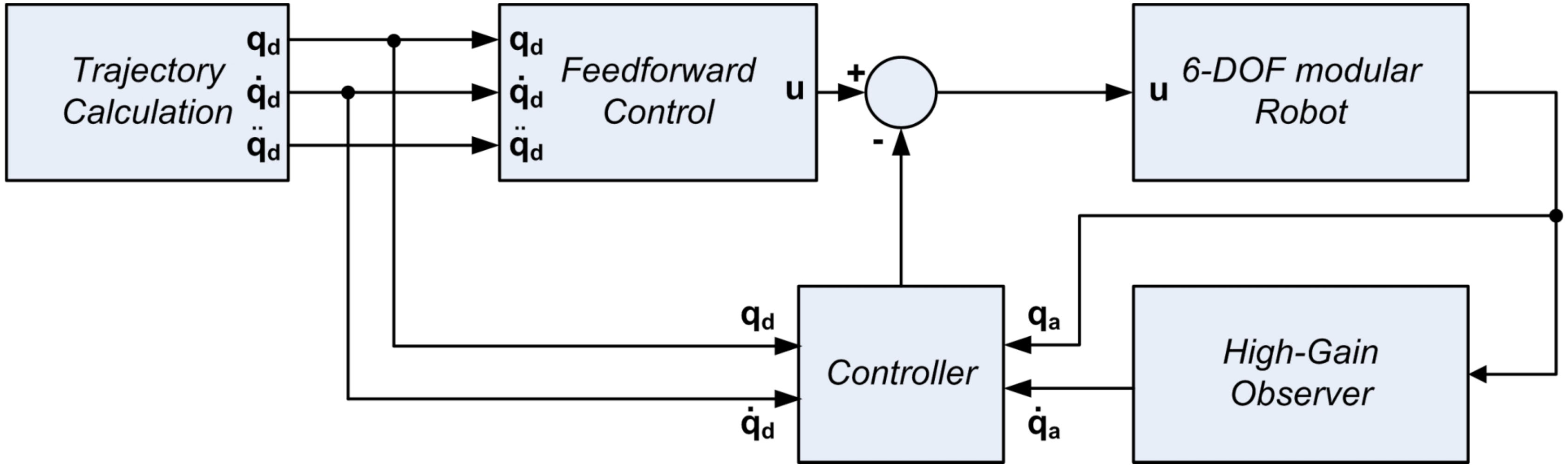


Selected Examples

- Reconfigurable robot arm control
  - Modular design → mechatronic components

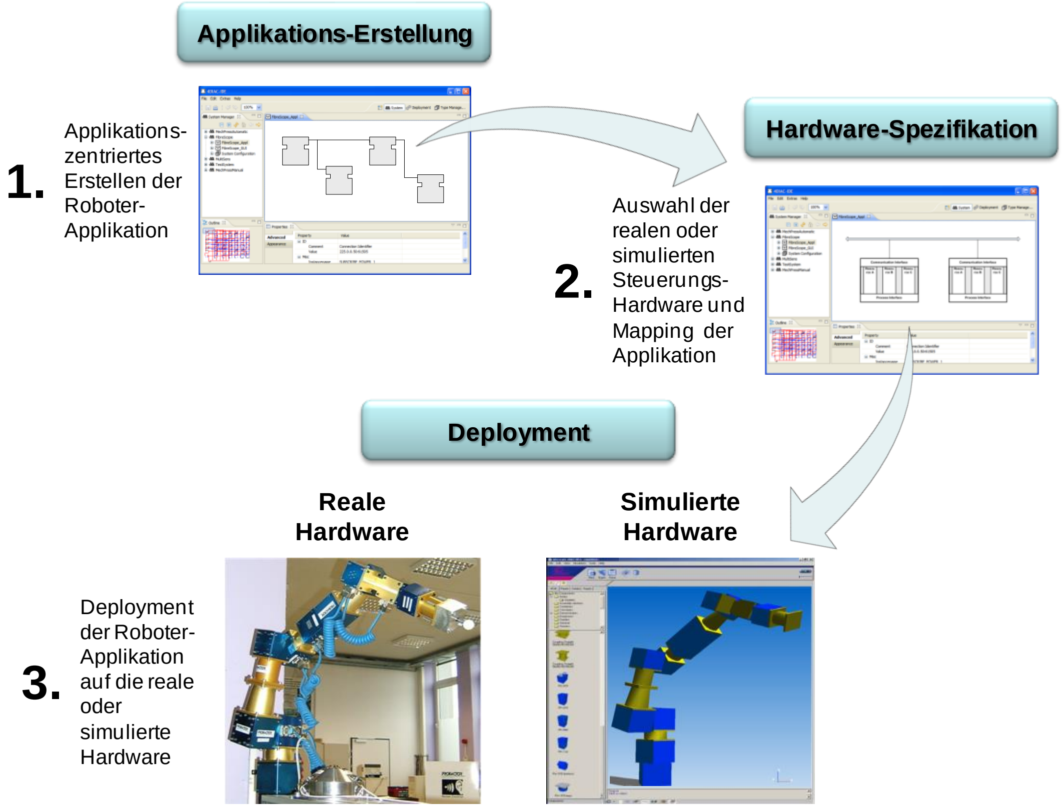
Selected Examples

- Reconfigurable robot arm control
  - Control architecture



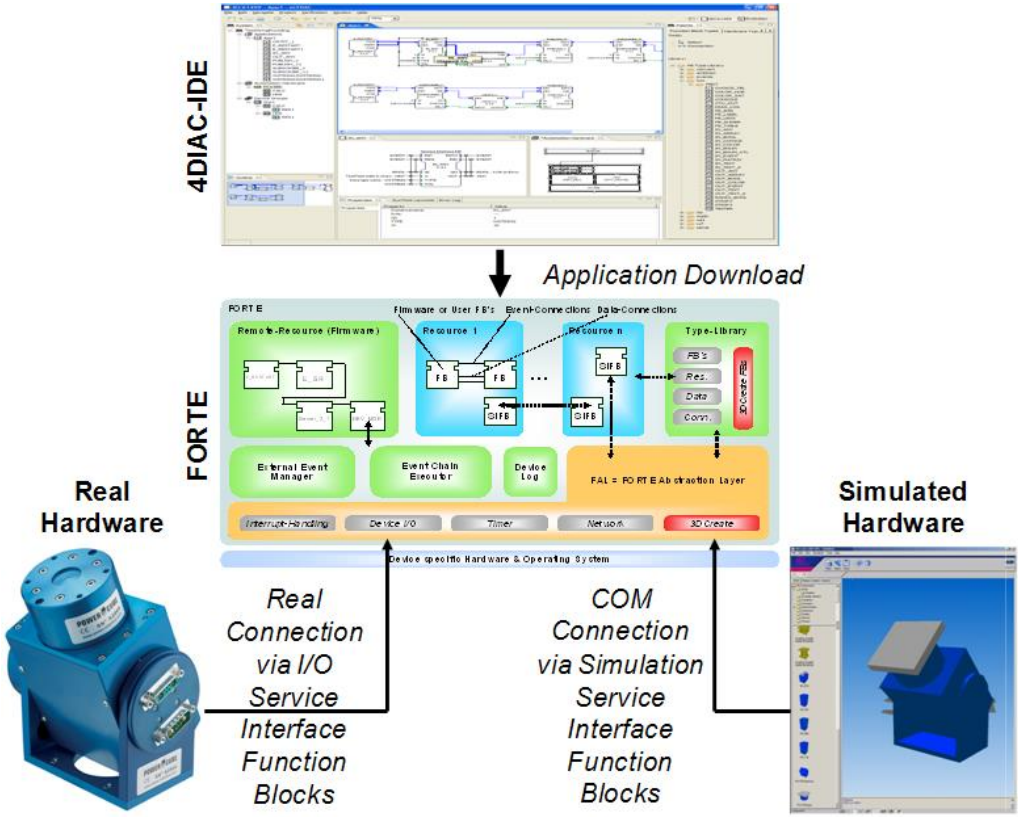
Selected Examples

- Reconfigurable robot arm control
  - Validation through reconfiguration



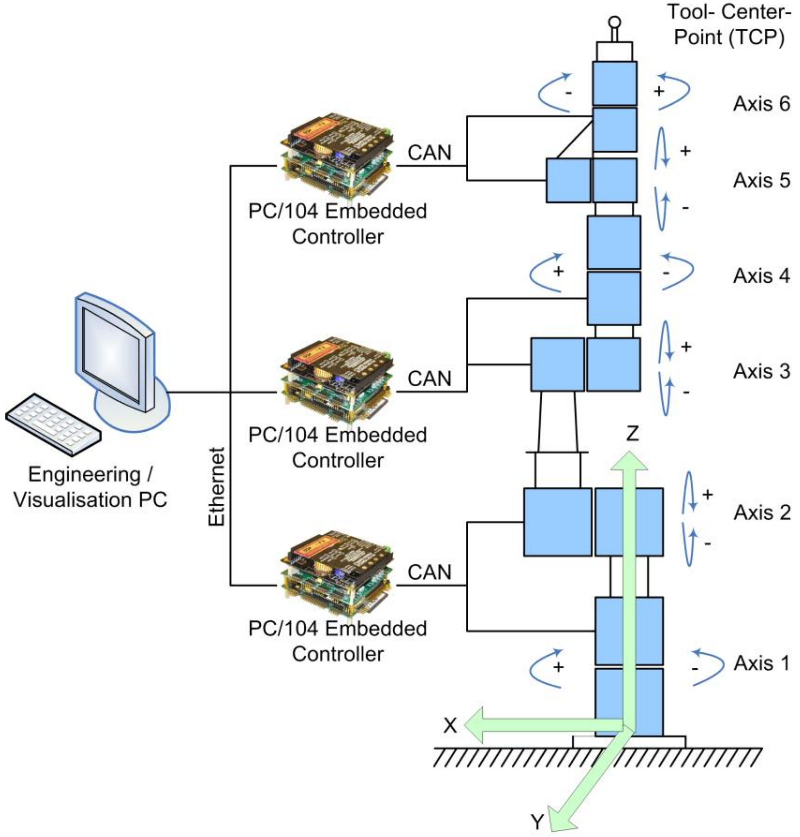
Selected Examples

- Reconfigurable robot arm control
  - Validation through simulation



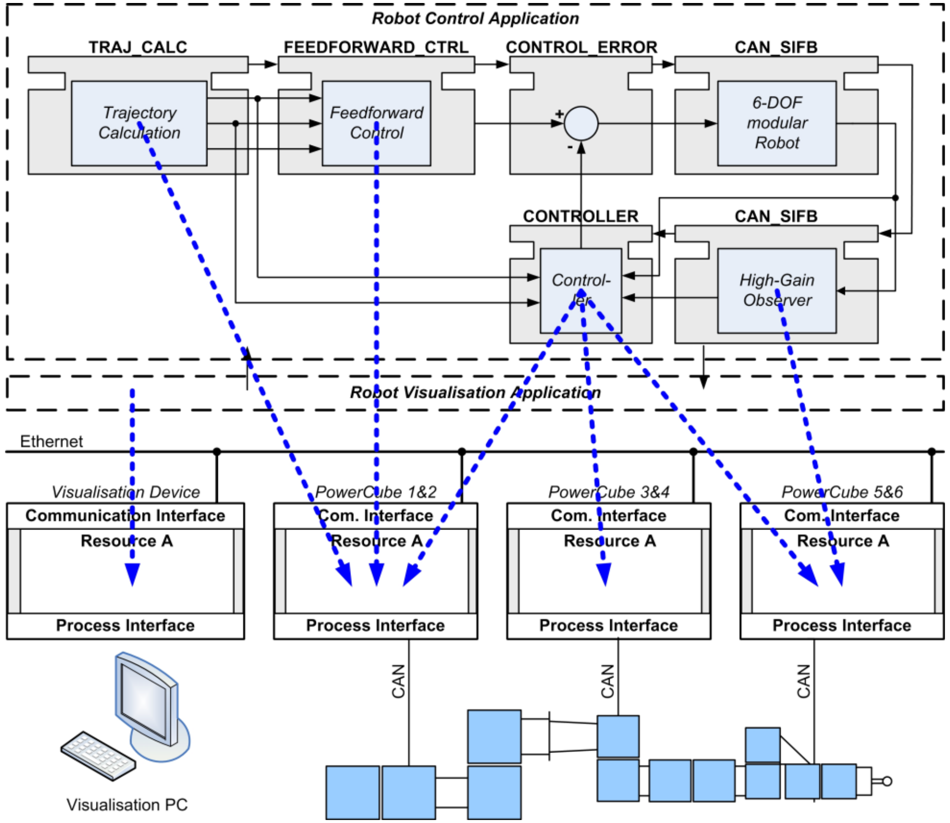
Selected Examples

- Reconfigurable robot arm control
  - Distributed control based on IEC 61499 – hardware setup



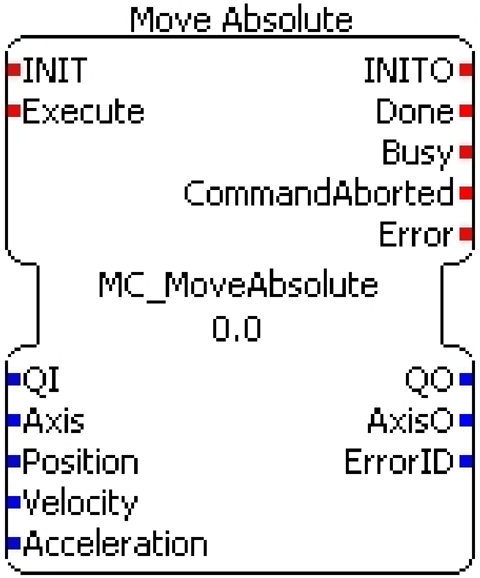
Selected Examples

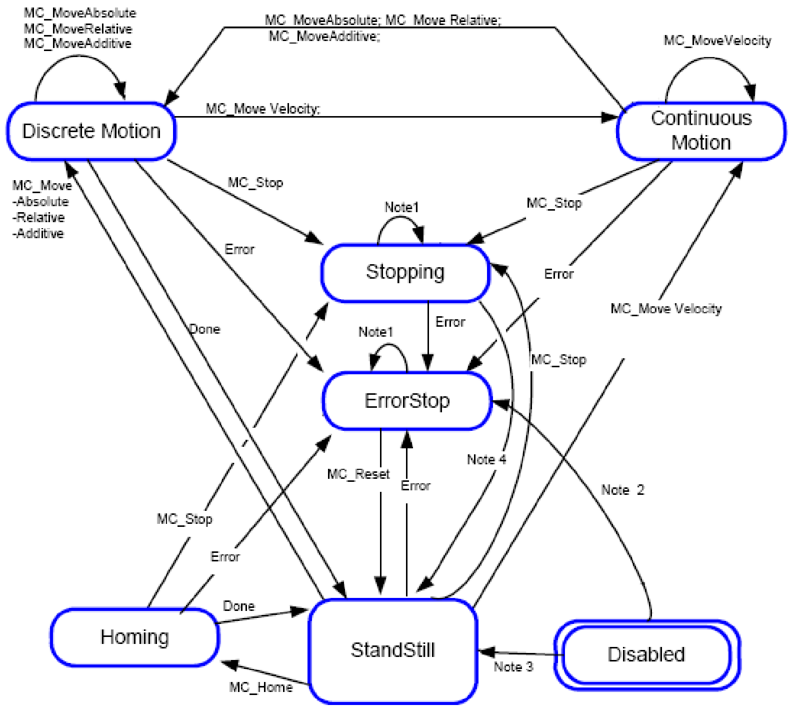
- Reconfigurable robot arm control
  - Distributed control based on IEC 61499 – system model



Selected Examples

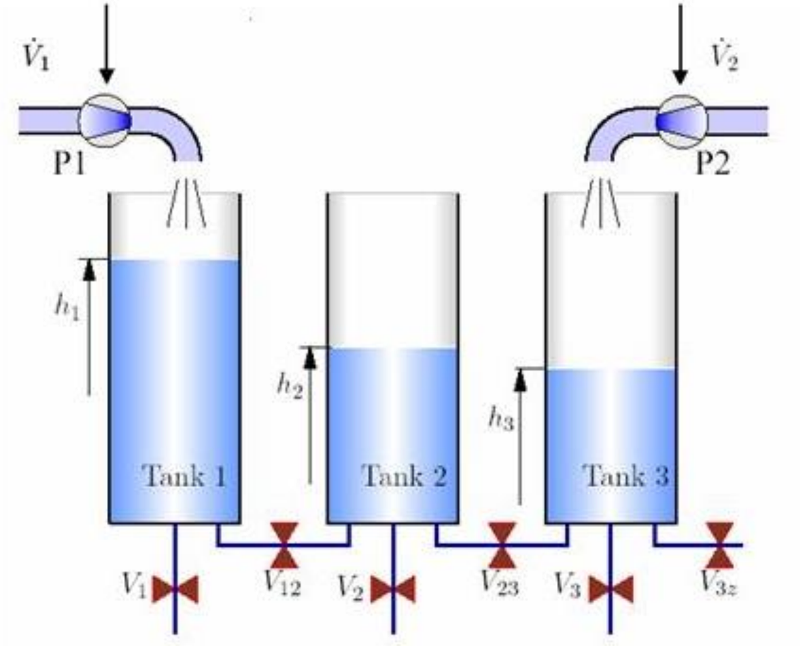
- Reconfigurable robot arm control
  - Distributed control based on IEC 61499 – hardware setup
    - PLCopen-based IEC 61499 motion control library





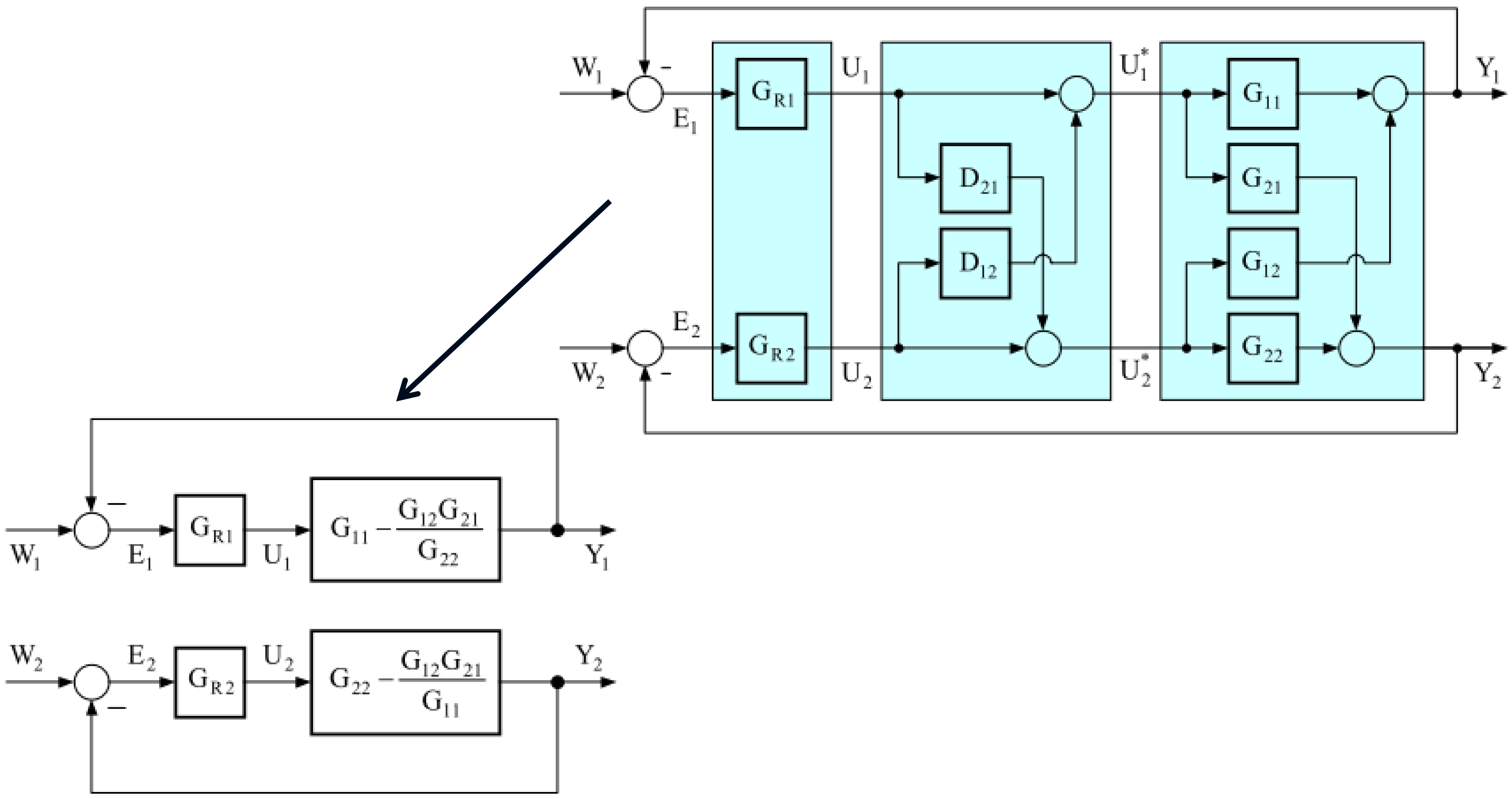
Selected Examples

- Three tank control – process overview



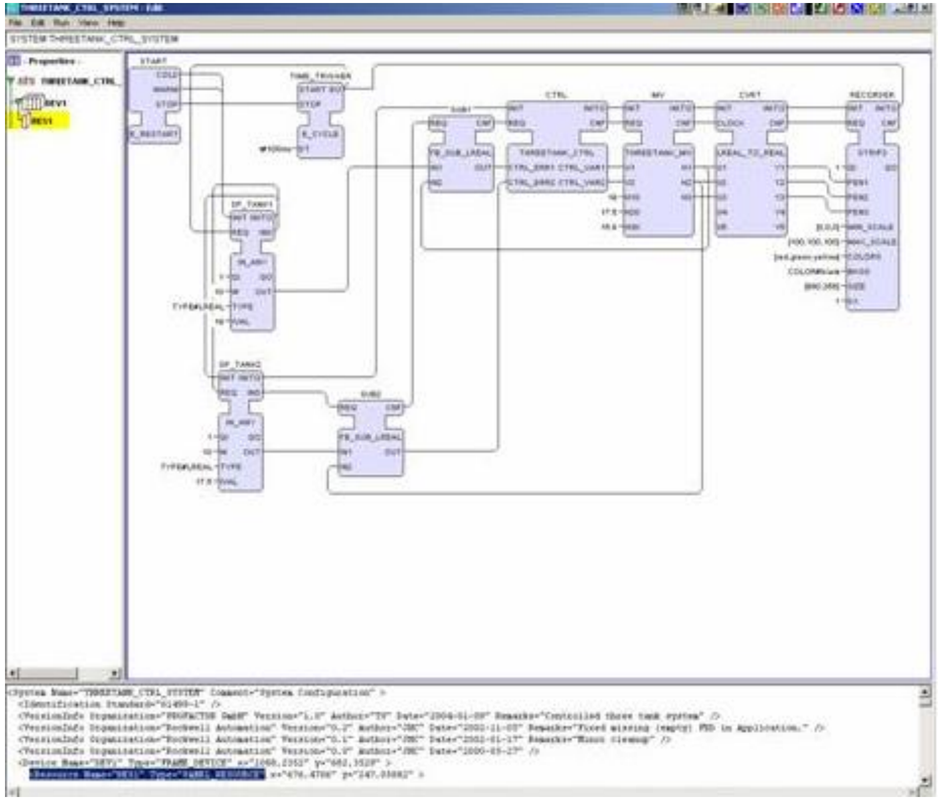
Selected Examples

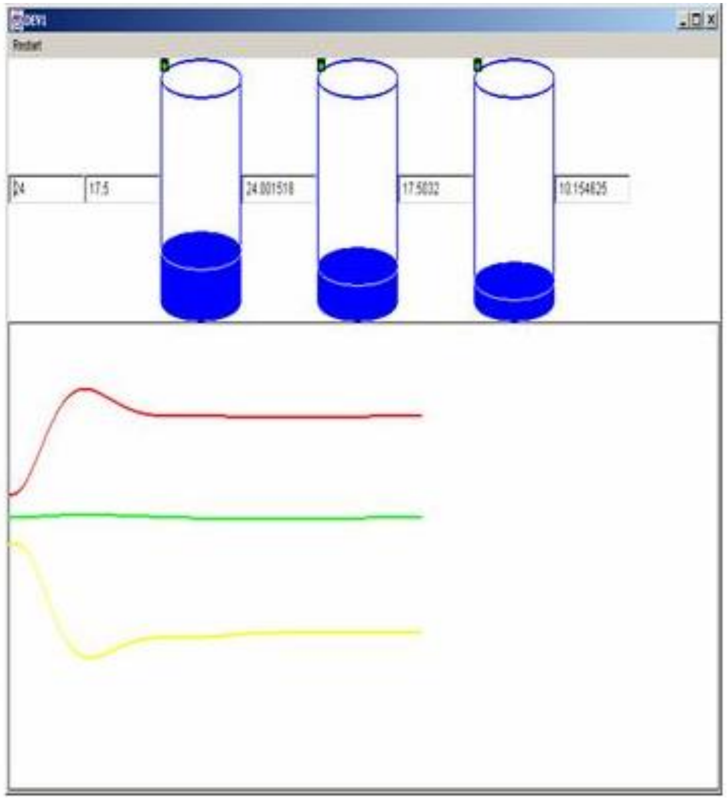
- Three tank control – control concept



Selected Examples

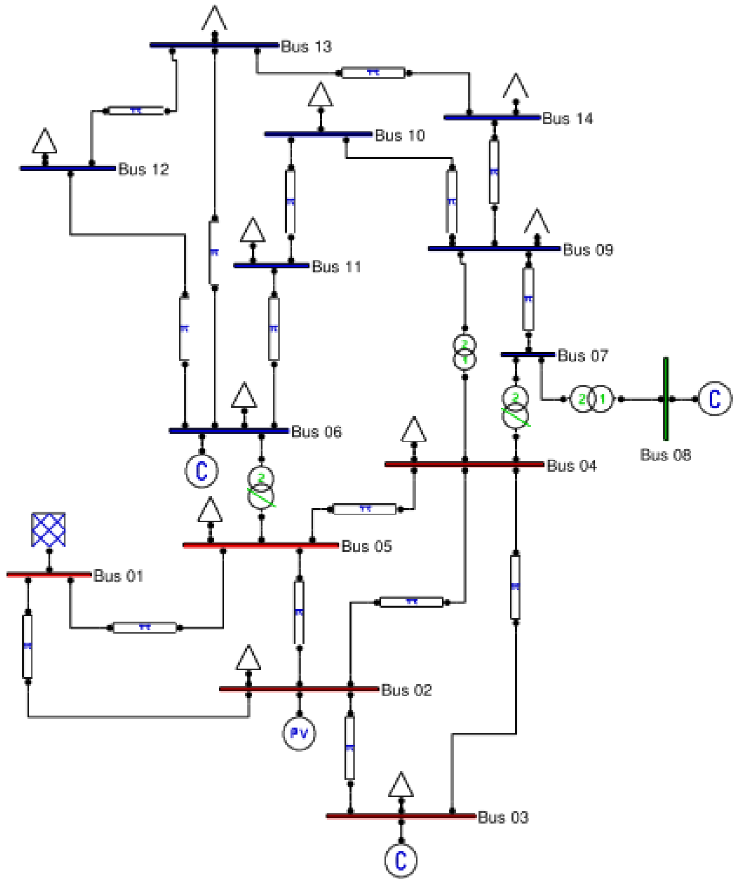
- Three tank control – control concept implemented in IEC 61499
  - Including plant and control model





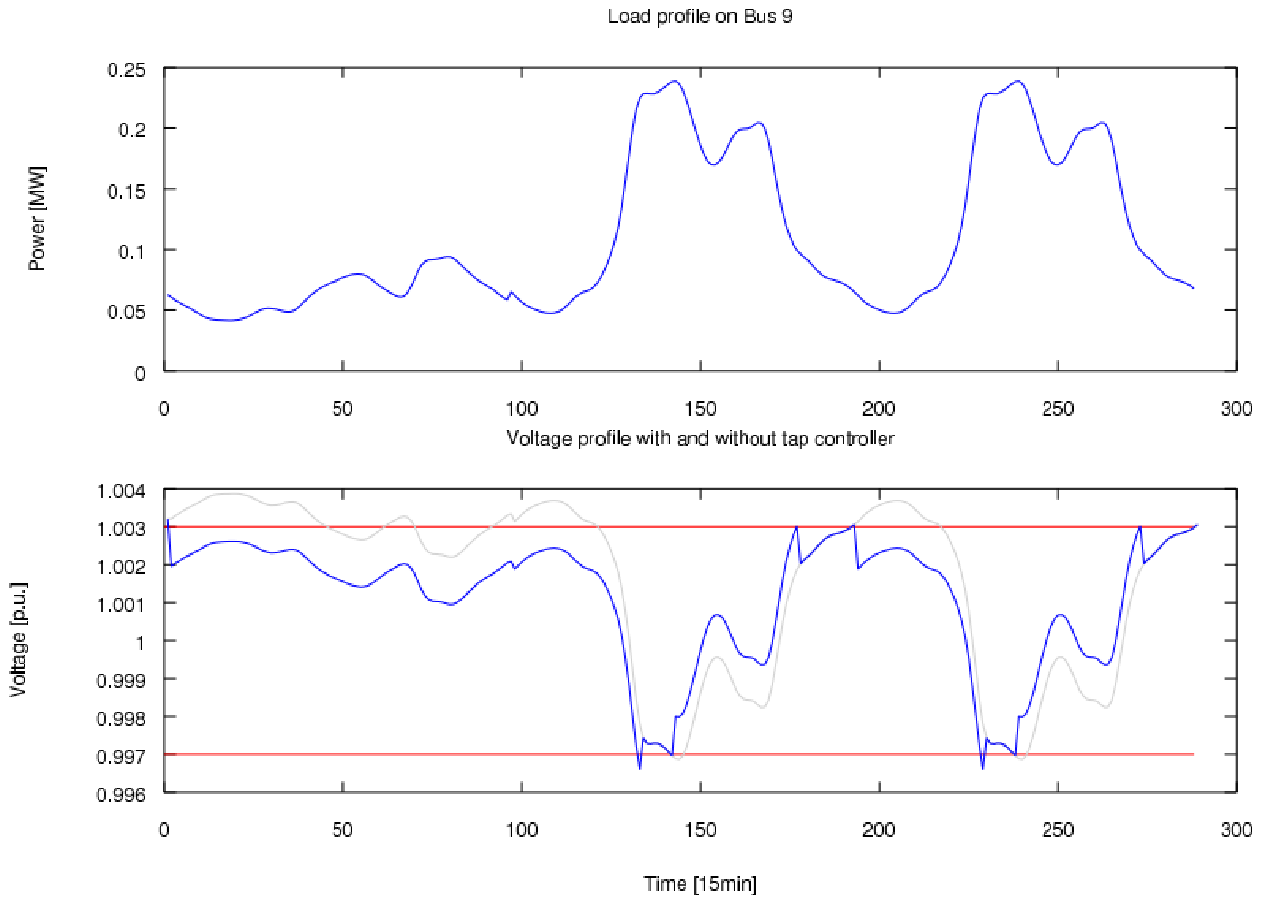
Selected Examples

- Tap-changer control (with power system simulation)



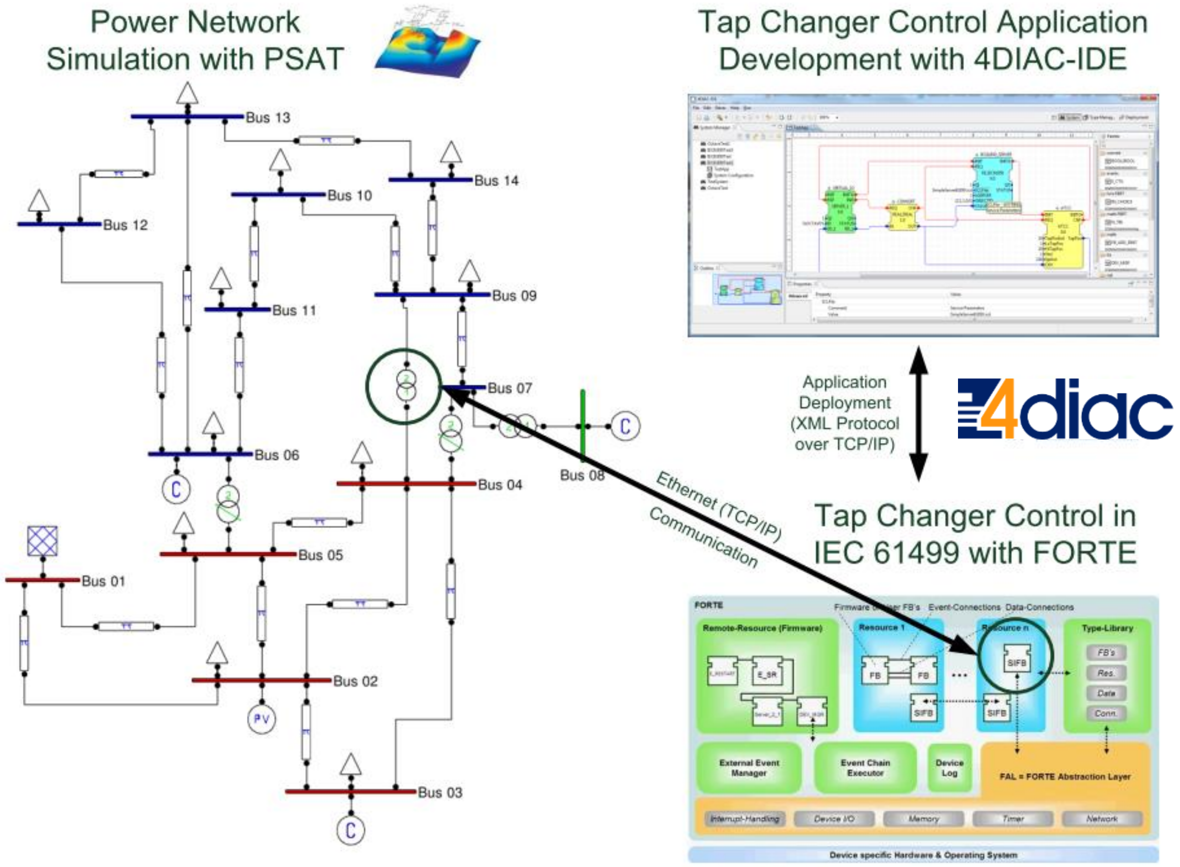
Selected Examples

- Tap-changer control (with power system simulation)



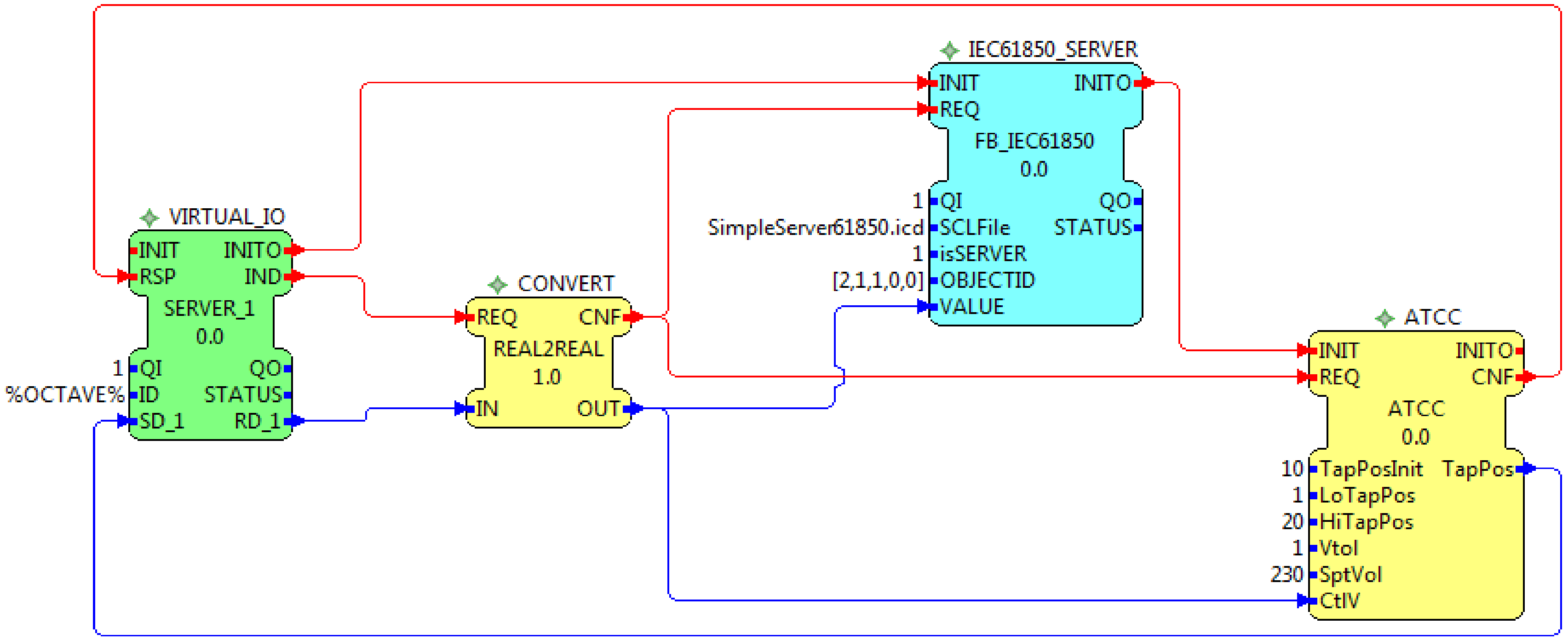
Selected Examples

- Tap-changer control (with power system simulation)



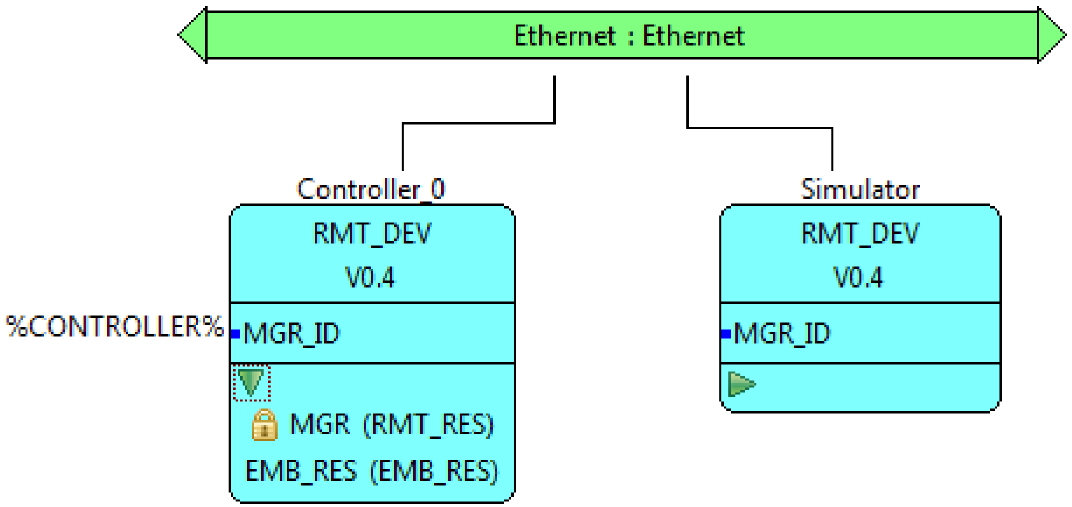
Selected Examples

- Tap-changer control (with power system simulation)
  - IEC 61499 application model



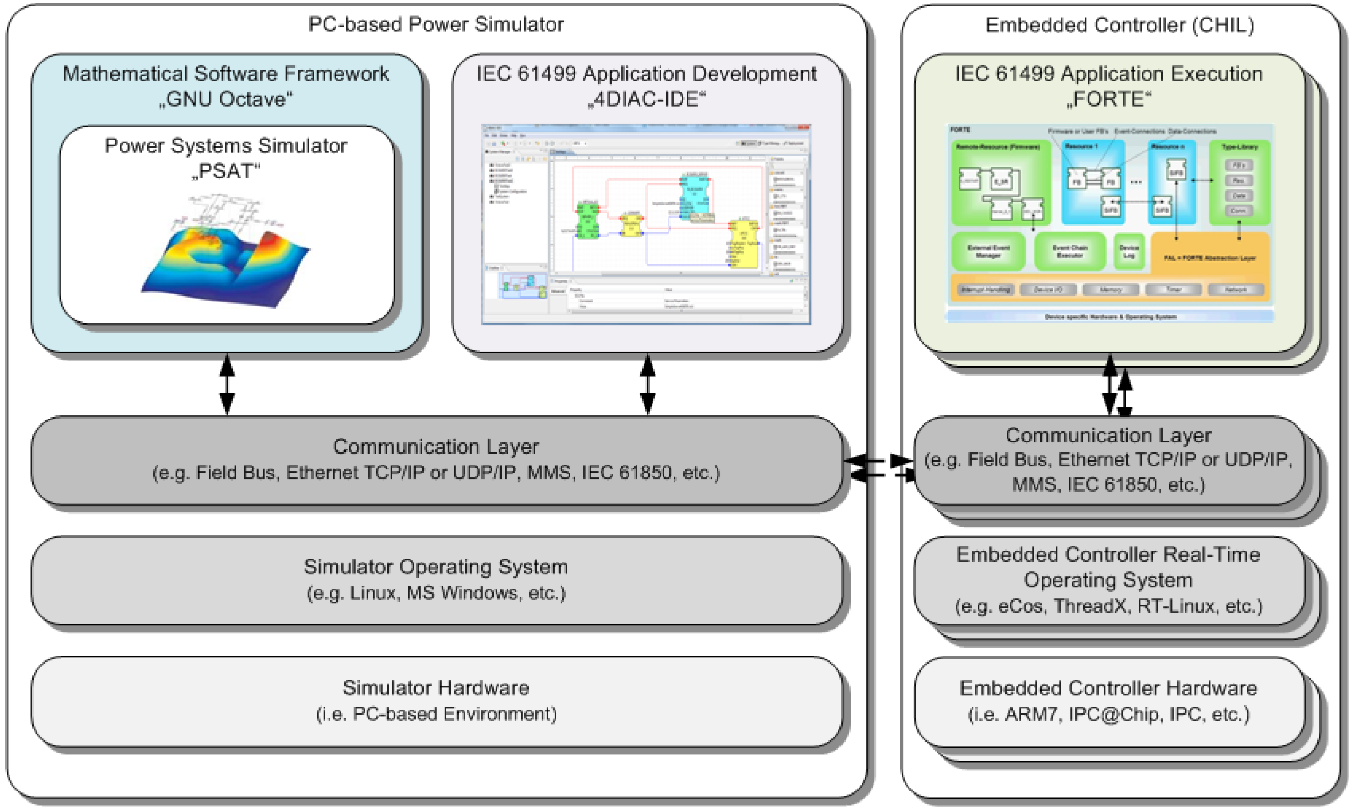
Selected Examples

- Tap-changer control (with power system simulation)
  - IEC 61499 system model



Selected Examples

- Tap-changer control (with power system simulation)
  - Controller-Hardware-in-the-Loop setup

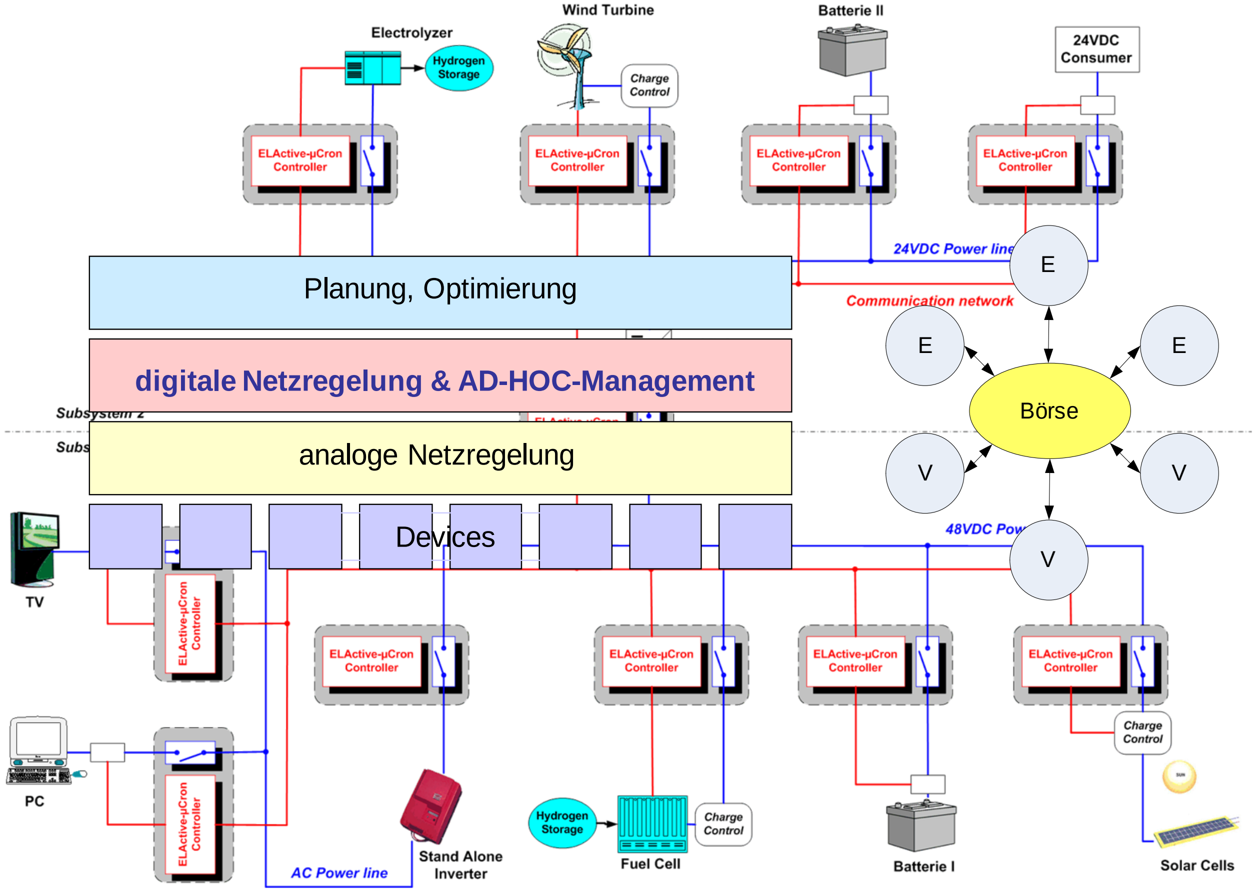


Selected Examples

- Micro grid control
  - Distributed control
    - Goal
      - Distributed control using IEC 61499
      - Energy management for islanded micro grid
    - Distributed approach
      - “Stock market” for producer (distributed generators) and consumer (loads)

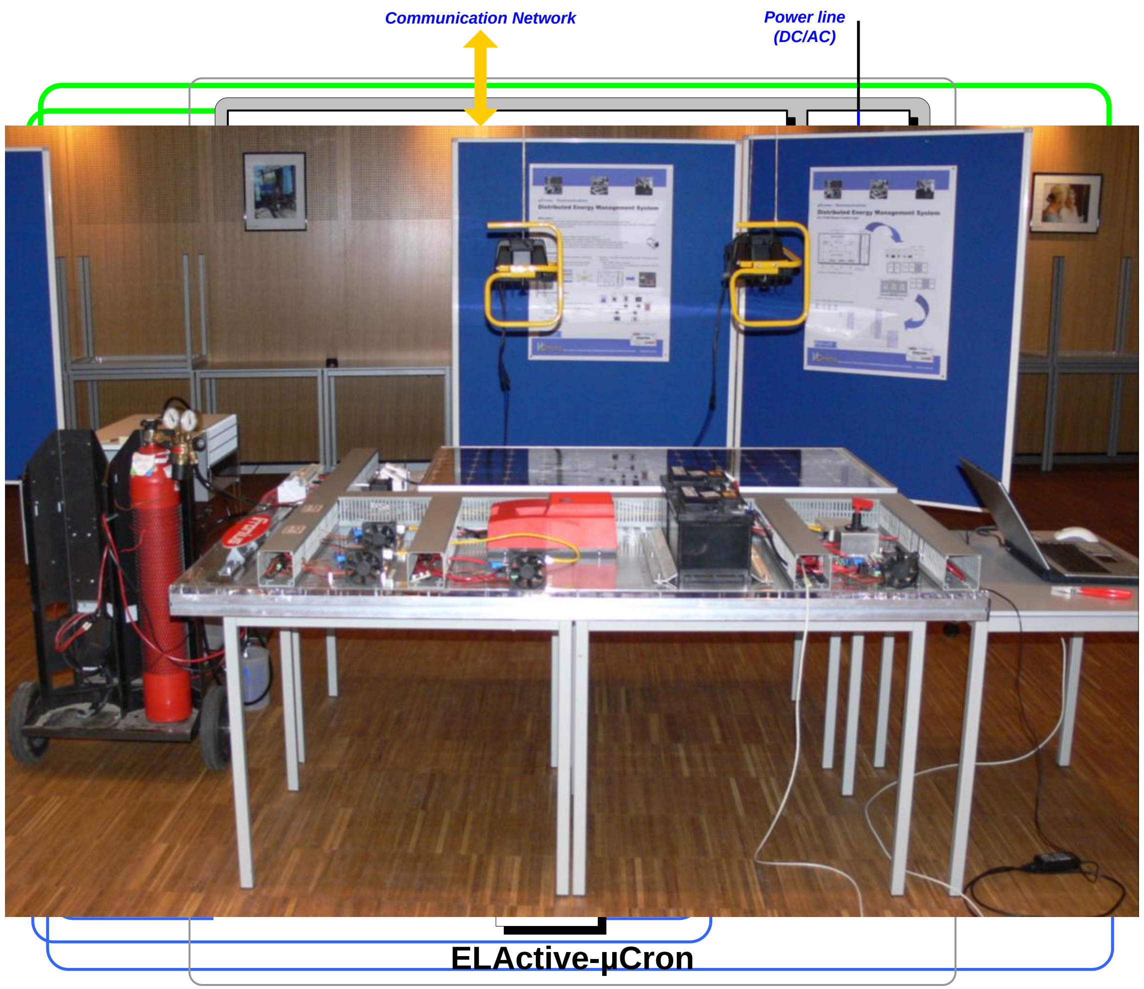
Selected Examples

- Micro grid control



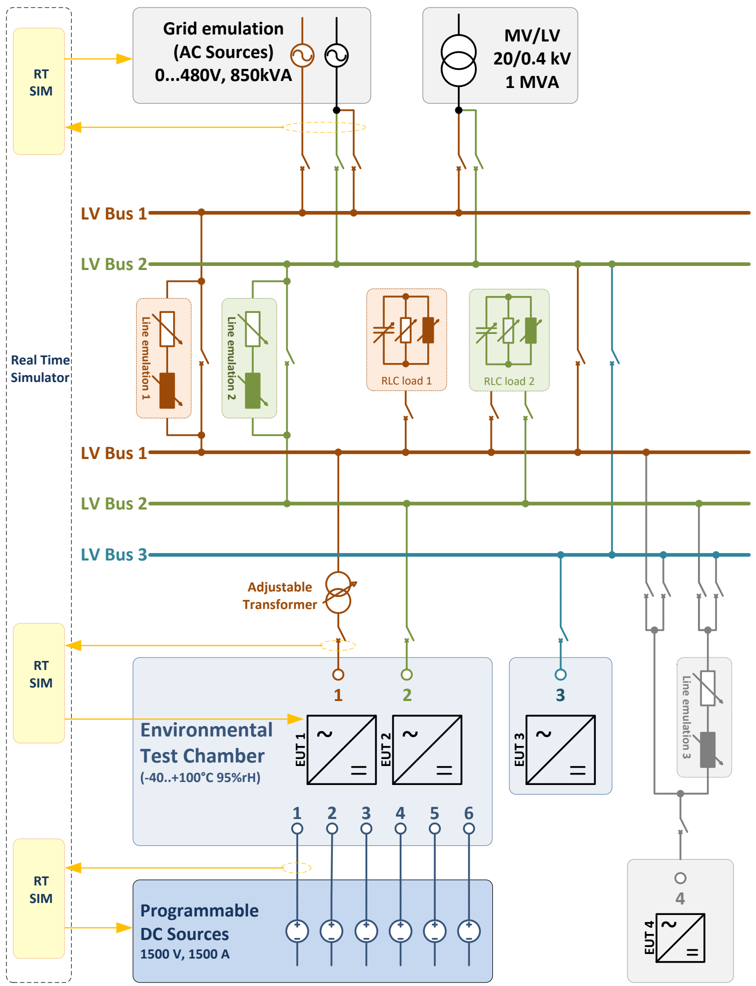
Selected Examples

- Micro grid control



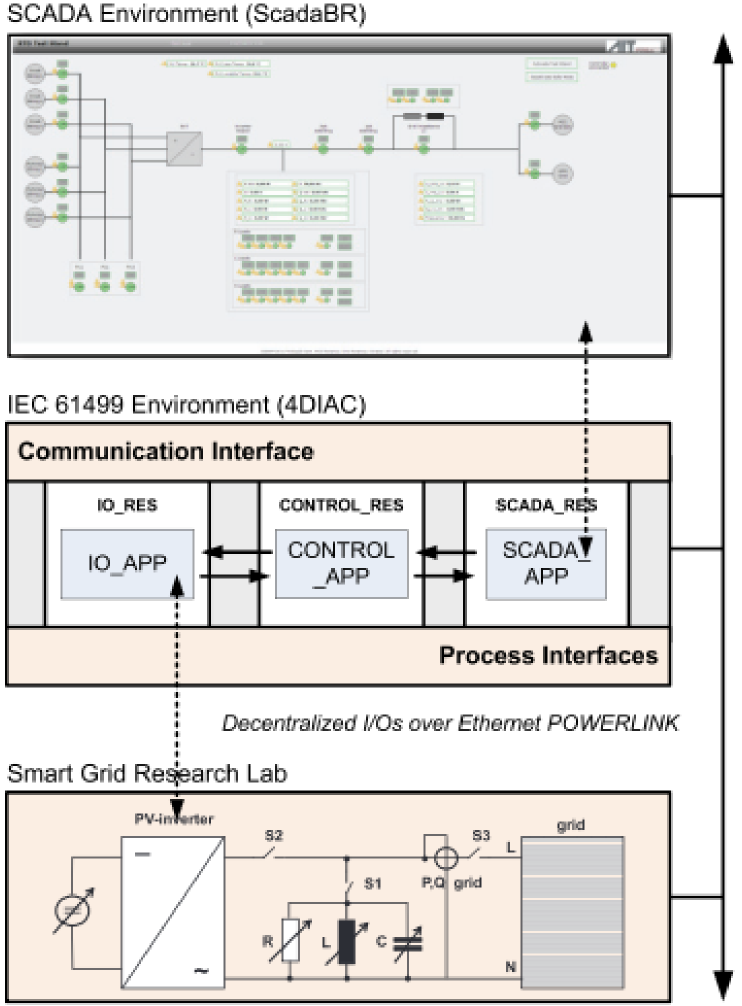
Selected Examples

- AIT SmartEST lab automation
  - Focus on research and testing of …
    - DER components
    - DER components system integration and system control
    - P-HIL based DER inverter system integration research



Selected Examples

- AIT SmartEST lab automation
  - Automation architecture
    - SCADA Layer
      - Superior control functions
      - Alterations straightforward
    - Control Layer
      - Basic control functionality
      - Software alterations possible, but not necessary
    - Hardware Layer
      - Proprietary hardware
      - No access to software

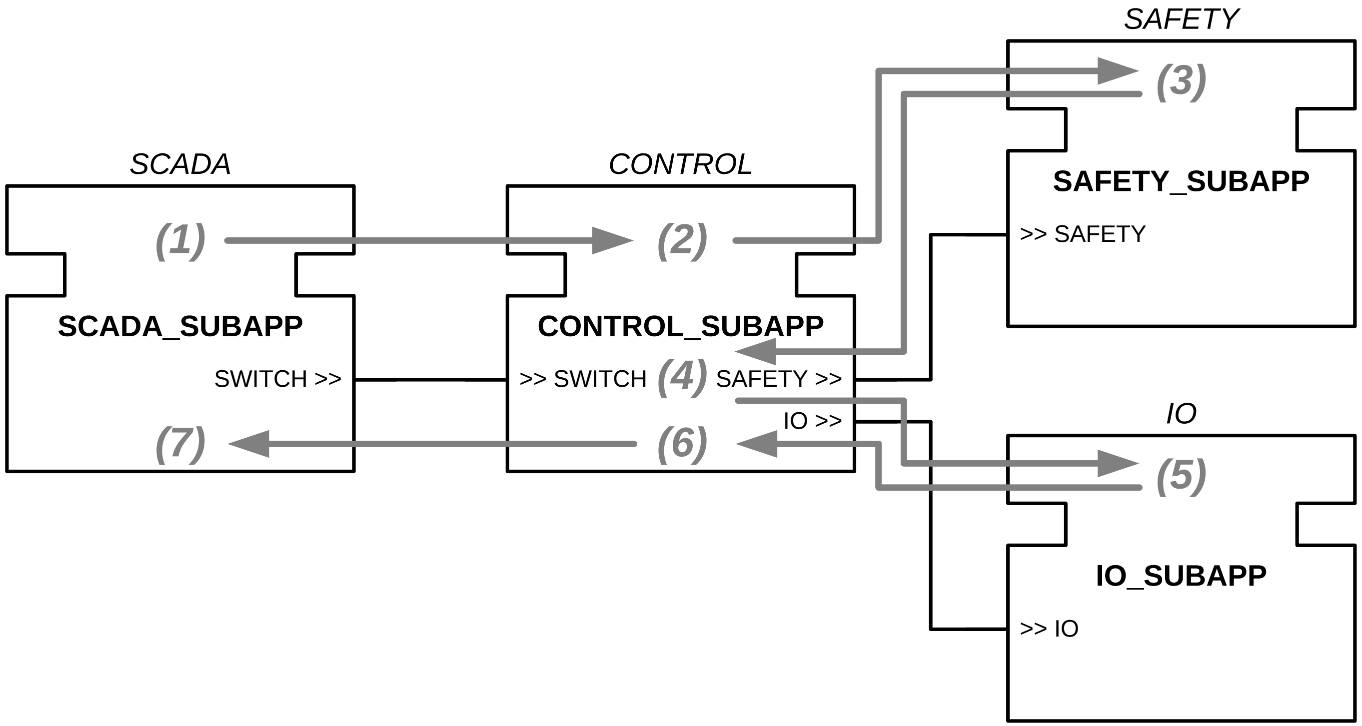


Selected Examples

- AIT SmartEST lab automation

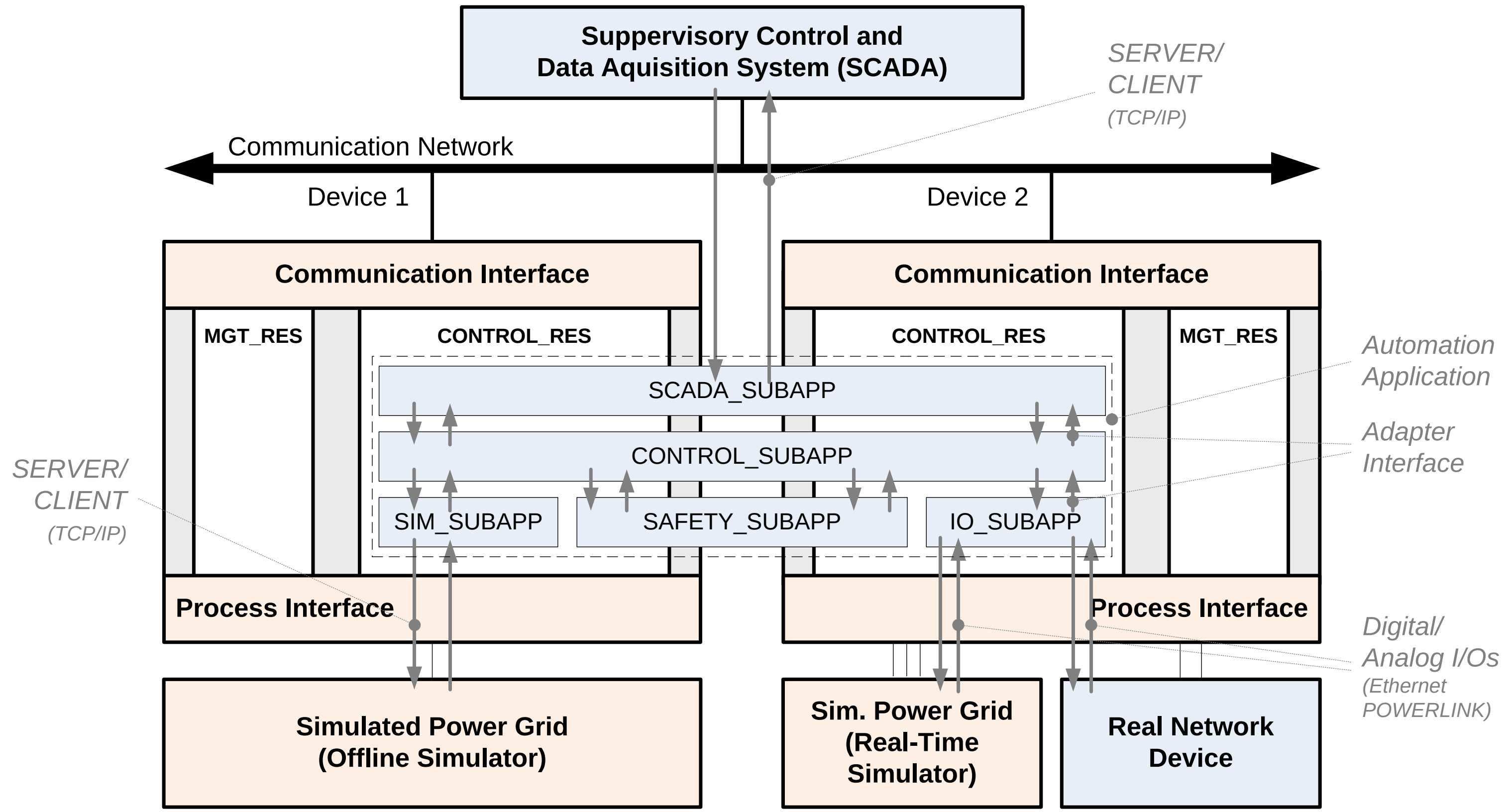
Selected Examples

- AIT SmartEST lab automation
  - IEC 61499 application model (high-level view)
    - More than 2000 data points (1300 I/Os, 700 measurements channels)



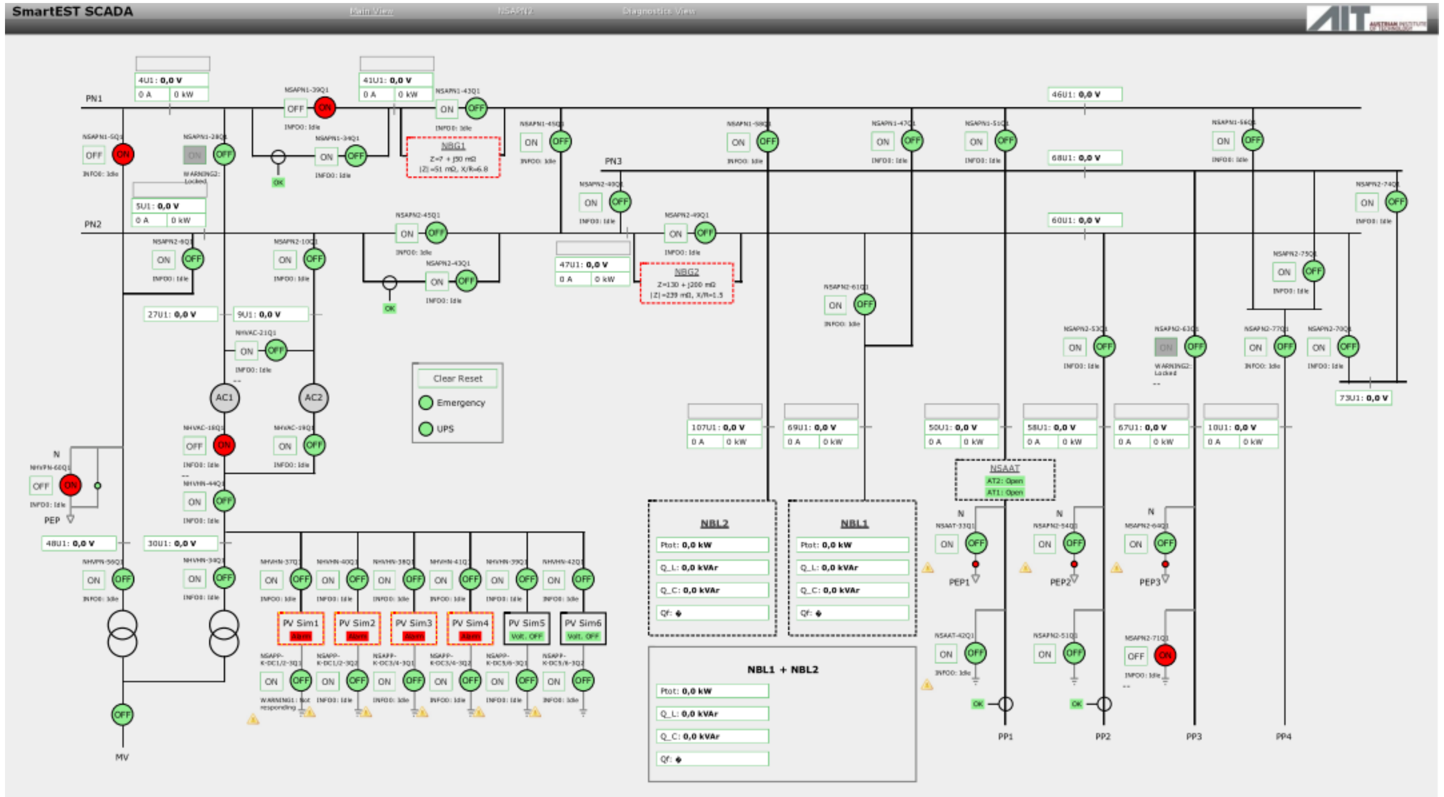
Selected Examples

- AIT SmartEST lab automation
  - IEC 61499 system model



Selected Examples

- AIT SmartEST lab automation
  - HMI / SCADA interface



Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

5. Discussion, Open Questions, etc.

Discussion, Open Questions, etc.

Designing Field Level Agents with IEC 61499

IEC 61499 Reference Model for Distributed Industrial Automation

6. Related Literature and References

Related Literature and References

- Standard
  - IEC 61499-1, Function Blocks - Part 1: Architecture
  - IEC 61499-2, Function Blocks - Part 2: Software tool requirements
  - IEC 61499-4, Function Blocks - Part 4: Rules for compliance profiles
- Quick overview
  - Eclipse 4diac – IEC 61499 101
  - Holobloc – Overview of the standard
  - IEC 61499 on Wikipedia
  - IEC 61499.de

Related Literature and References

- User group
  - [UniversialAutomation]
- Free and open-source tools
  - Eclipse 4diac
  - FBDK
- Commercial tools
  - Rockwell Automation / ISaGRAF
  - Schneider Electric / nxtControl
  - Fbuilder

Related Literature and References

- Selected books
  - Alois Zoitl & Robert Lewis, “Modeling control systems using IEC 61499, 2nd Edition”, The Institution of Engineering and Technology, 2014
  - Valeriy Vyatkin, “IEC 61499 Function Block for Embedded and Distributed Control Systems Design, Third Edition”, O3NEIDA – International Society of Automation, 2015
  - Alois Zoitl, “Real-time Execution for IEC 61499”, O3NEIDA – International Society of Automation, 2008
  - Alois Zoitl & Thomas Strasser, “Distributed Control Applications: Guidelines, Design Patterns, and Application Examples with the IEC 61499”, CRC Press, 2016

Privatdoz. DI Dr. Thomas Strasser

Senior Scientist
Electric Energy Systems
Center for Energy

AIT Austrian Institute of Technology GmbH
Giefinggasse 2 | 1210 Vienna | Austria
thomas.strasser@ait.ac.at | http://www.ait.ac.at

Univ.-Prof. DI Dr. Alois Zoitl

Professor for Cyber-Physical Systems
for Engineering and Production
LIT Open Innovation Center

Johannes Kepler University Linz
Altenberger Straße 69 | 4040 Linz | Austria
alois.zoitl@jku.at | http://www.jku.at