A Model-Driven Approach to Embedded Control System Implementation

Jan F. Broenink,

Marcel A. Groothuis, Peter M. Visser, Bojan Orlic

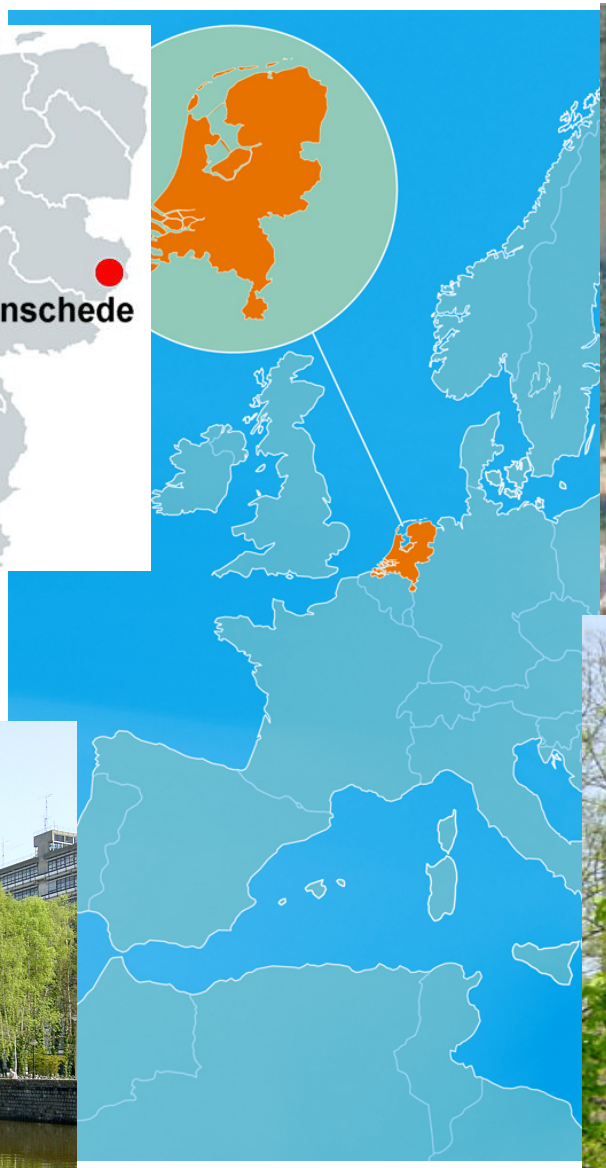
Control Engineering,

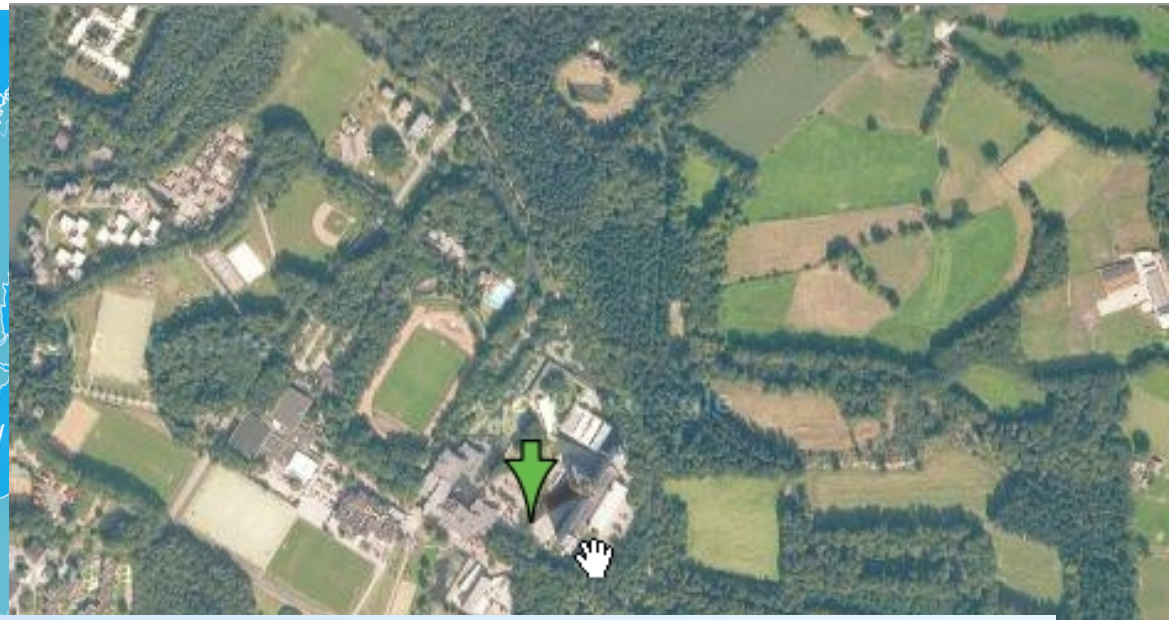
CTIT, Faculty EE-M-CS,

University of Twente, Enschede, Netherlands

e-mail: J.F.Broenink@utwente.nl, web: www.ce.utwente.nl/bnk

University of Twente, Enschede, Netherlands





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Electrical Engineering

- **University of Twente**
  - **Enschede**
  - **2500 personnel; 6500 students**
  - **5 Faculties:**
    - » **Behavioral Sci; Management & Governance**
    - » **Engineering Techn. Science & technology; EEMathCS**
- **EE**
  - **Microsystems; Biomedical Syst; Telecom;**
  - **Control & Mechatronics; Embedded Systems**
  - **CE**
    - » **2.2 full; 2.2 assoc; 10 PhD; 15-20 MSc**
    - » **www.ce.utwente.nl**

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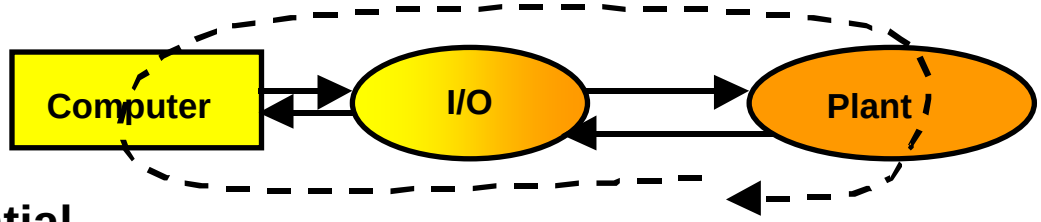
Overview

- **Introduction**
  - Embedded Control Systems
  - Goal and Benefit
- **Design Approach**
  - Mechatronic Systems, Embedded Control Software
  - Model-based design; Verification by Simulation
- **Modeling formalisms**
  - Port-based (bond) graphs – plant
  - CSP diagrams – software
- **Embedded Control System Implementation**
  - Controller Models, Workflow
  - Stepwise Refinement
  - Tools, Distributed Simulation Framework
- **Case**
  - Try-outs at lab

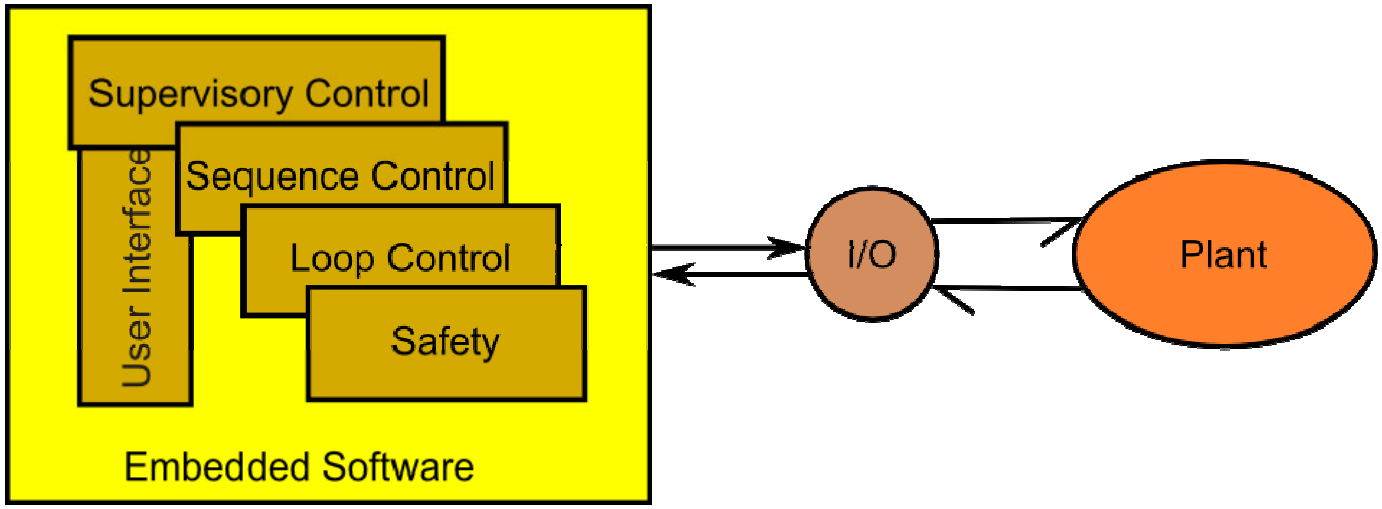
Embedded Control Systems

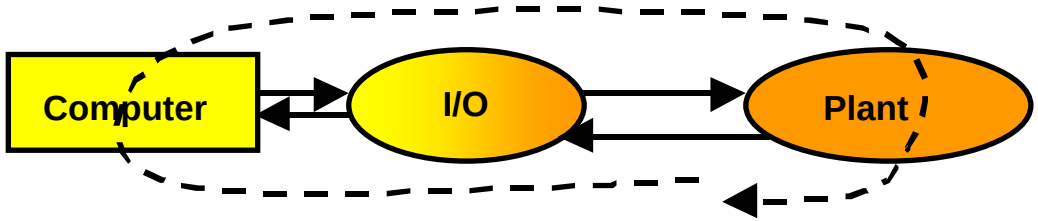


- **Essential properties**
  - Loop controllers hard real time
  - Dynamic behavior of plant essential
    - » Latency small compared to time constants plant
    - » Whole system must be considered
  - Intrinsically concurrent
- **Software**
  - User Interfacing, Data processing, Plant control (20-30% of code)
  - Reliable, safe, timing guaranteed
  - Triggering: bounded jitter (isochronous)
- **Hardware**
  - Computer hardware & I/O interfacing
  - Programmable devices
  - Distributed and heterogeneous
- **Plant**
  - Machine, Sensors, Actuators, Power Amplifiers

Layered Structure of Controllers

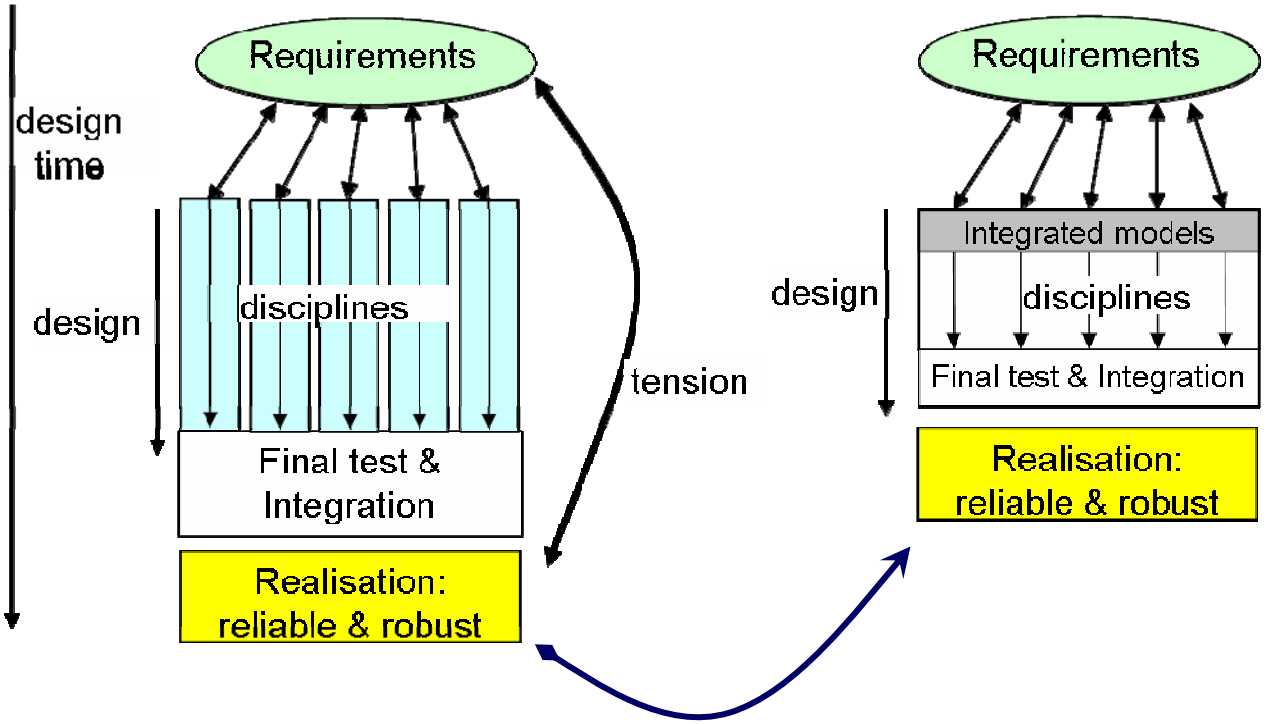
- **Timing**
  - **Hard real time**
    Safety,
    Loop Controllers,
    Sequence Controllers
    (set point generators)
  - **Soft real time**
    Sequence Controllers,
    Supervisory Controller,
    User Interface





Goal, Benefit, Approach

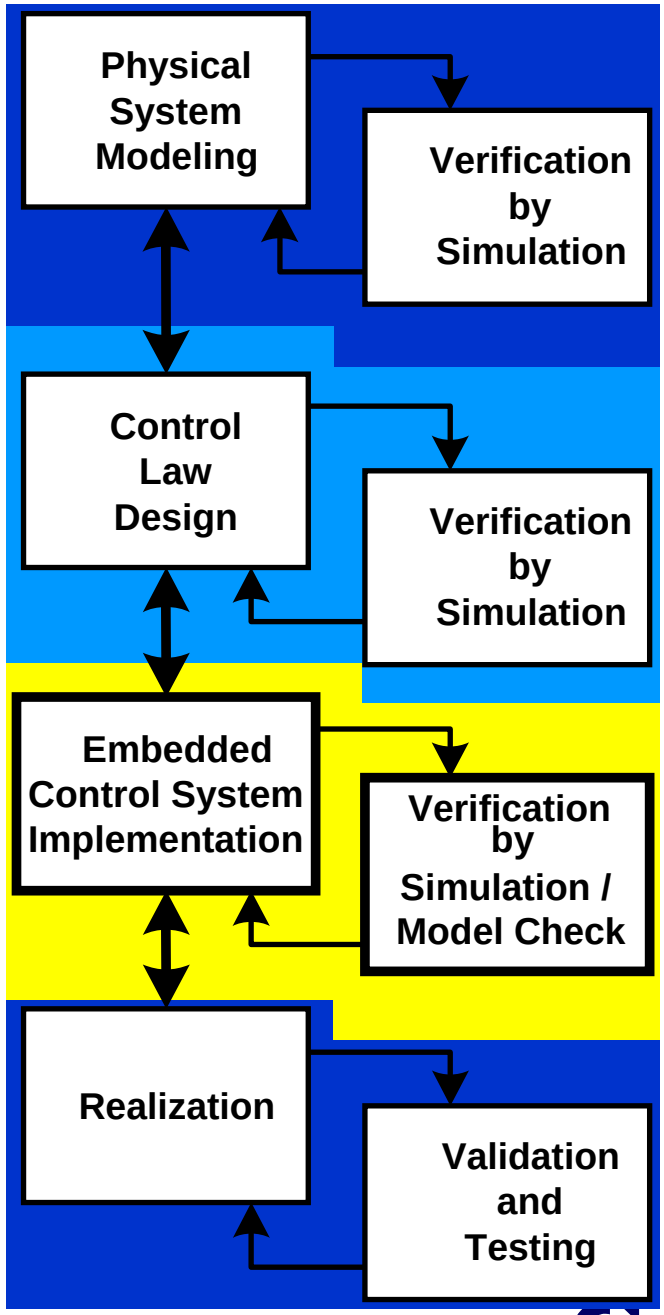
- **Problem**
  - **Developing Reliable and Robust Embedded Control Software is too costly and too time consuming.**
- **Reasons**
  - **Complexity**
  - **Heterogeneity**
  - **Lack of Predictability**
  - **Late Integration**
- **Approach**
  - **Virtual prototyping = Simulation**
  - **Model-level integration discipline-specific issues**
  - **Property-preserving code generation**



Shorten design time
Better quality product

Design Approach, Tools

- **Tools needed**
  - Extendable / updatable software
  - Total system (embedded + embedding!)
- **Embedded Control Systems**
  - Dynamic behavior of plant
  - Layered structure of controllers
  - Stepwise refinement
    - » Physical Systems modeling
    - » Control law Design
    - » Embedded Control System Implementation
      - Gradually enhance laws to code
    - » Realization
  - Verification by Simulation & Formal Checking

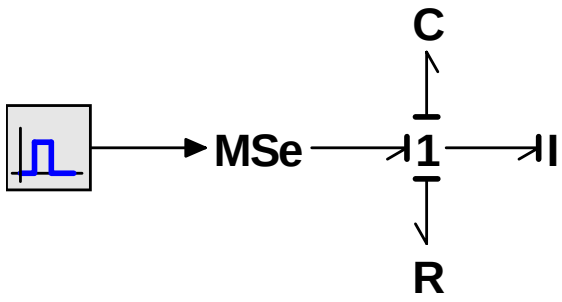


Used Model Formalisms

- **Demands**
  - **Overview** - **Hierarchy**
  - **Reusability** - **Interfaces,**
    - **Implementation independent of connection**
  - **Simulate-ability** - **Total model!**
- **Essential solution**
  - **Object Orientation, Components**
  - **Port-based Interfaces**
- **Choices**
  - **CSP Diagrams**
    - » **Software structure, CSP-based, DFD, compositional**
  - **VHDL**
    - » **Configurable: design I/O functionality as if it were software**
  - **Port-based (Bond) Graphs**
    - » **Object-oriented physical systems modeling**

Port-based (Bond) Graphs – Plant

- **Bond Graphs**
  - Relevant dynamic behavior as diagram
    - » Directed graph: submodels & ideal connections
  - Domain-independent
    - » Analogies between physical domains
  - Restricted number of elements
    - » Per physical basic concept 1 bond-graph element

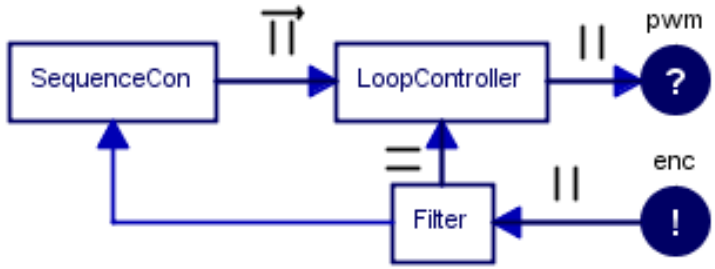


- **Encapsulation of contents**
  - Interface: ports with 2 variables
    - » (u, i): voltage & current; (F, v): force & velocity;
  - Equations as equalities (math. Equations)
    - » Not as algorithm: u = i * R -> u := i * R of i := u / R
- **Simulation (tool)**
  - Compile to differential equations (statements)
  - Simulation = repeatedly execution of statements

20-sim

CSP Diagrams – Software Structure

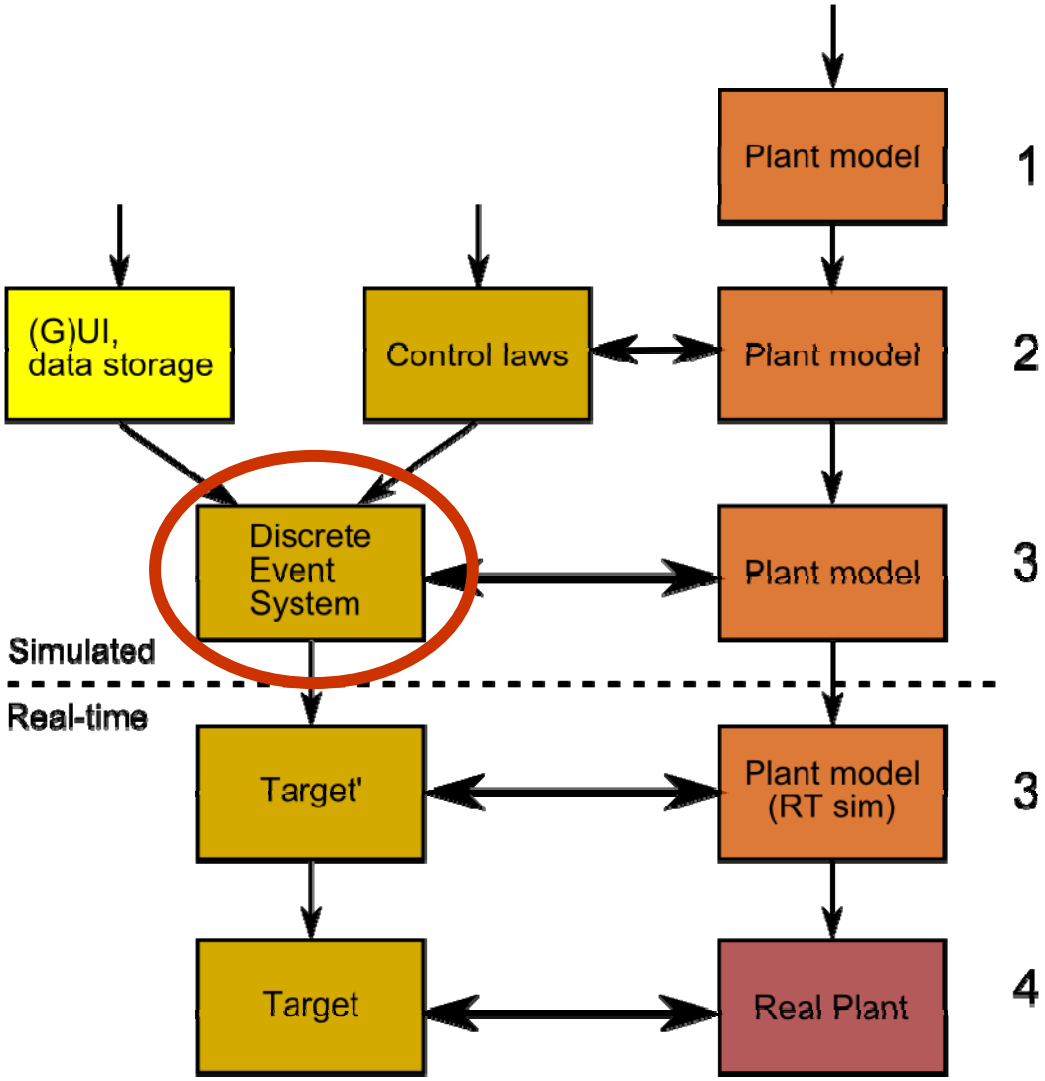
- **Dataflow diagrams - CSP**
  - Kind of block diagram
  - Communicating Processes
  - Connections (= channels) transport only
  - Formally verify-able
  - Theory: CSP (Hoare)
  - Checkers – FDR2



- **Encapsulation**
  - Implementation independent of communication
    - » Channel connections as ports
  - Scheduling at rendezvous: in application
- **Process operators**
  - PAR, ALT, SEQ
  - PRI-PAR, PRI-ALT, EXC
  - Compositional semantics
- **Events**
  - Atomic
  - Instantaneous: no duration
  - Variable v over channel c: c.v
  - Direction specific: in?x and out!x

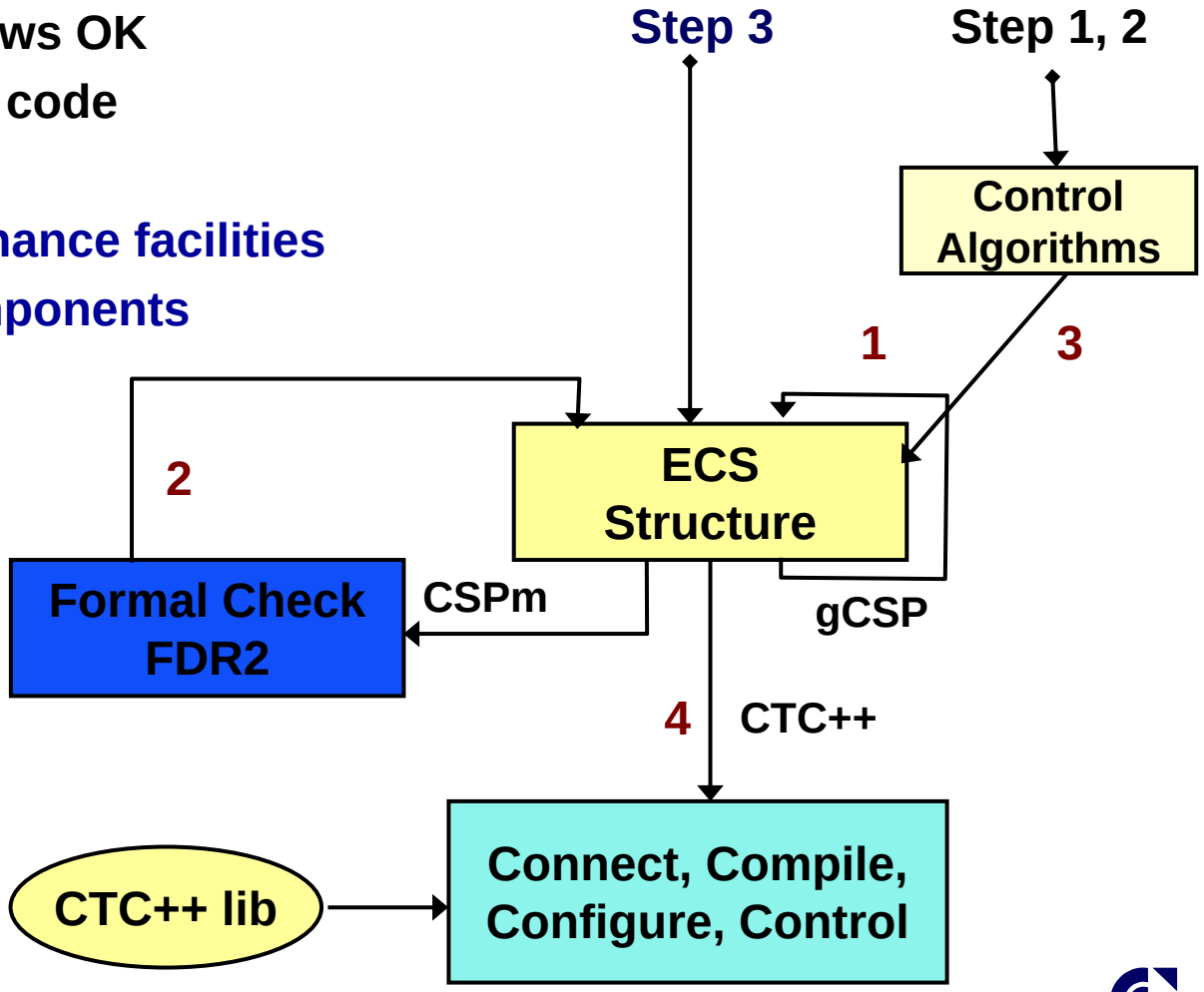
Embedded Control System Implementation

- **Models**
  - Controller (CSP) -> code on target
  - Plant (bond graphs) -> simulation
- **Co-simulation**
  - Discrete Event & Continuous Time
- **Steps in the method**
  1. Physical Systems modeling
  2. Control law Design
  3. Embedded Control System Implementation
  4. Realization



Embedded Control System Implementation II

- **Step 3 in the method**
  - Plant model OK; Control laws OK
  - Gradually enhance laws to code
    - » Integrate control laws
    - » Safety, error & maintenance facilities
    - » Capture non-ideal components

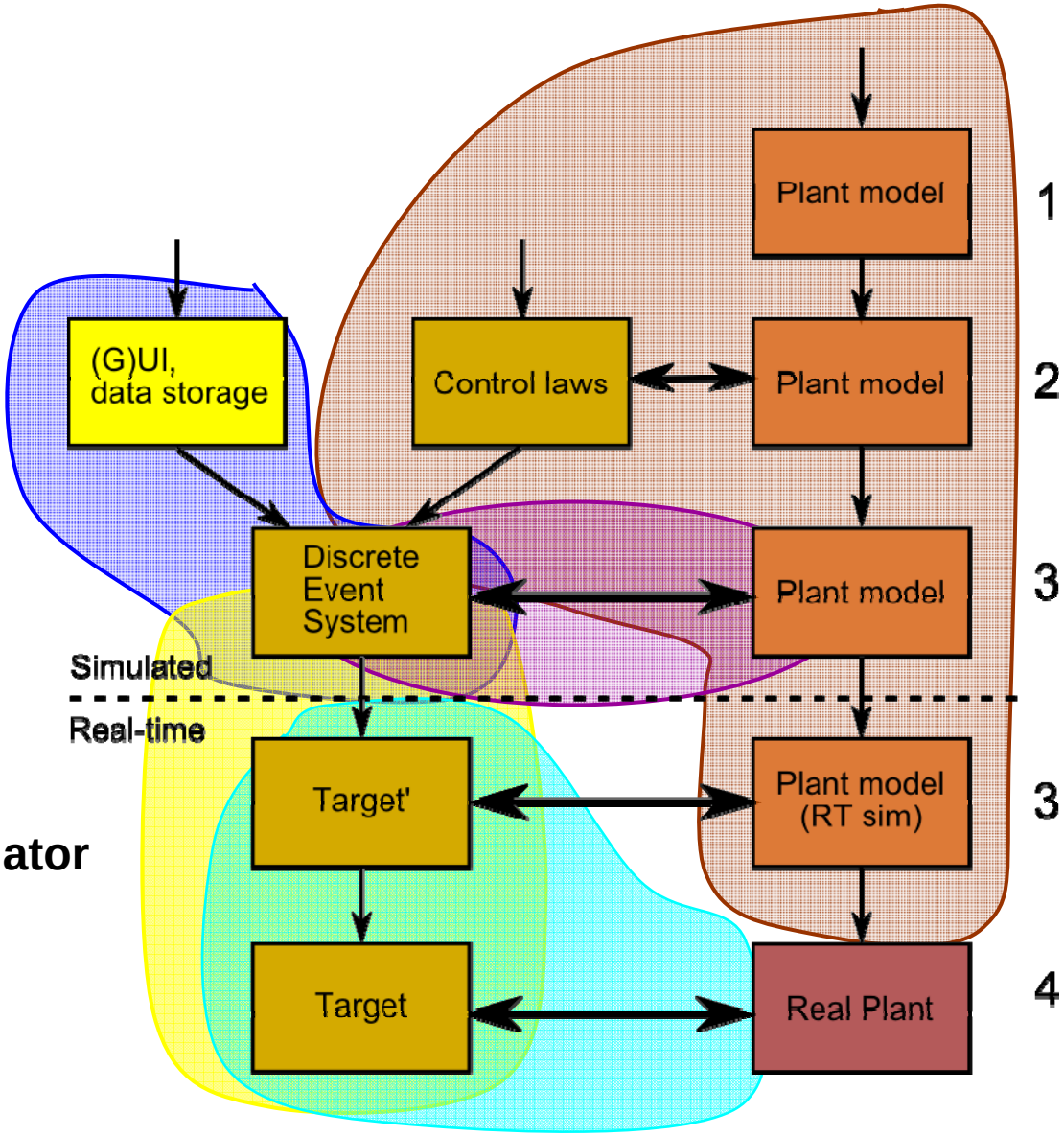


Working Order

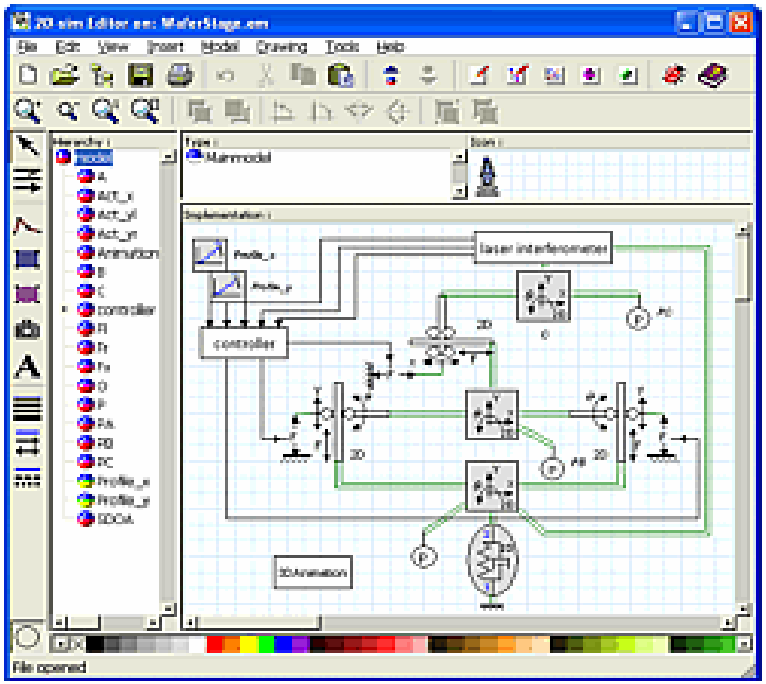
1. Internal checks
2. Formal Check process logic
3. Include (control) algorithms
4. Check target code

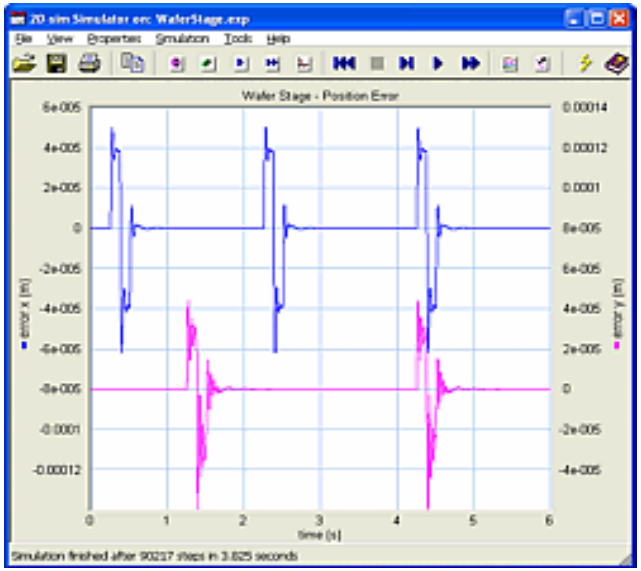
Tools

- **20-sim**
  - Bond Graphs, Block Diagrams
  - Continuous Time Simulator
- **gCSP**
  - CSP Diagrams
  - Software Structures
  - FDR2
- **CTC++**
  - CSP concurrency
  - Middleware
- **NWsim**
  - Discrete Event / Network Simulator
  - CTC++ based
- **ForSee (4C)**
  - Configure, Compile
  - Command, Control



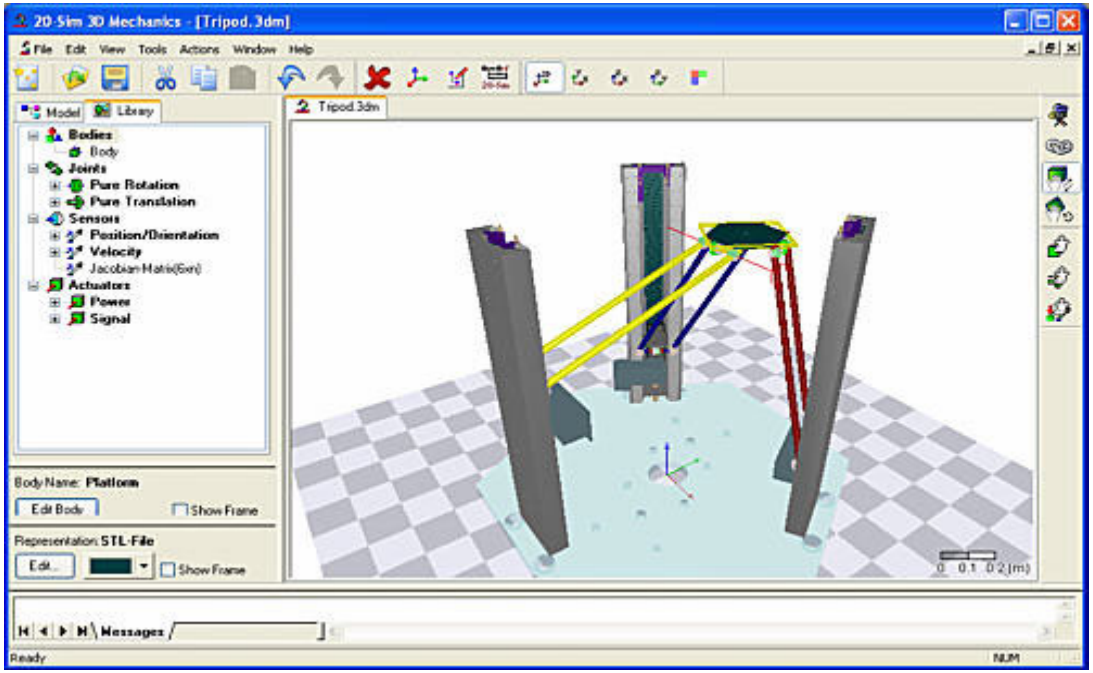
20-Sim





Modeling & simulation

- Bond graphs
- Ideal Physical Models
- Block Diagrams
- Continuous Time Simulation
- Animation
- Basic Controller Design
- Code Generation
  - » C (CTC++)
  - » Token Replacement
    - %NUMBER_OUTPUTS%
- Commercially Available



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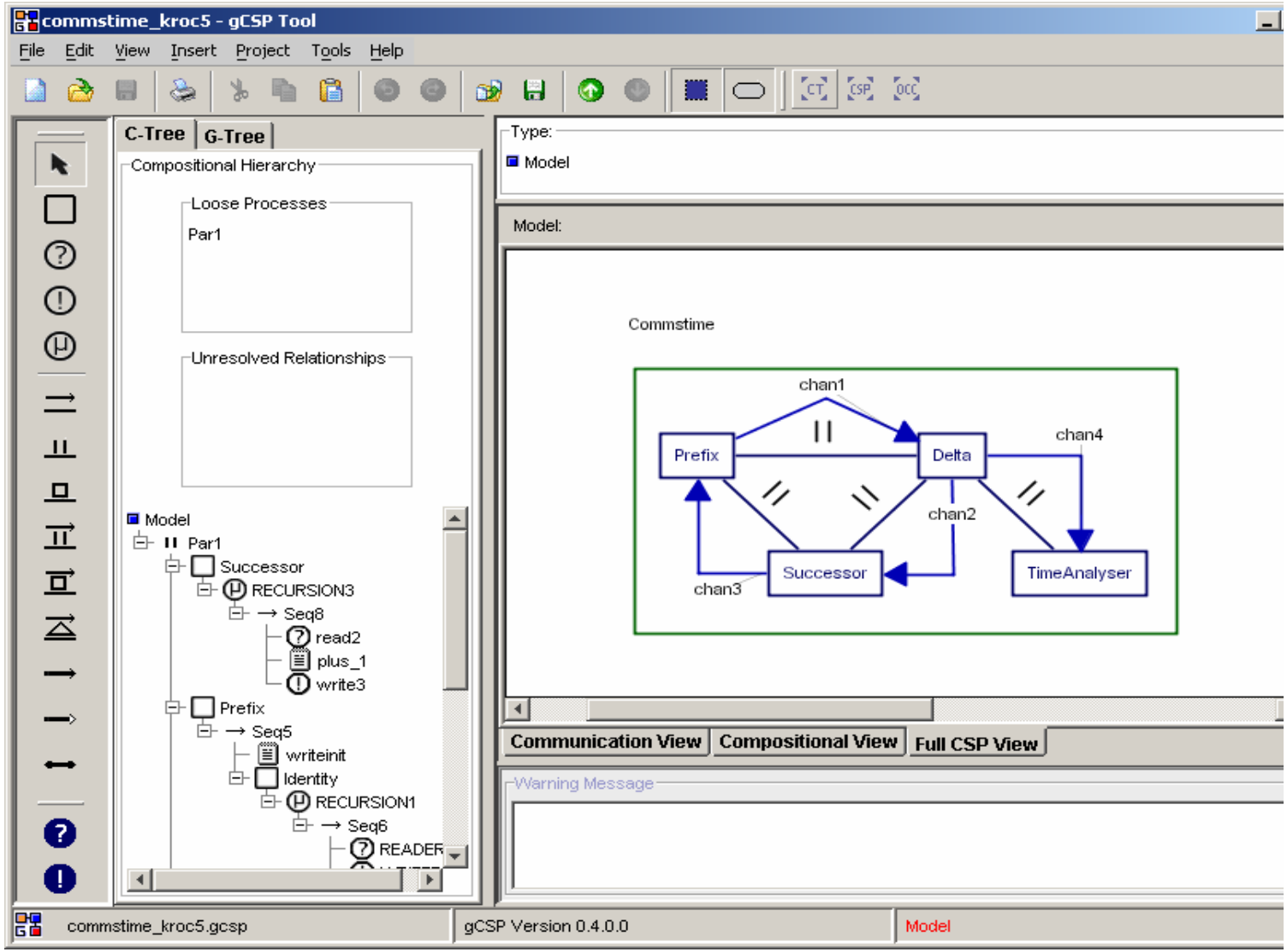
gCSP

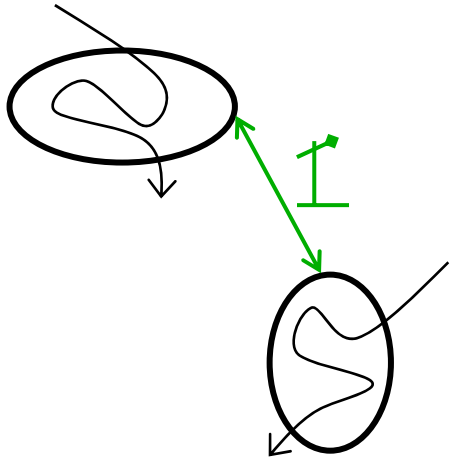
Parallel Software Modeling

- Software Structure
  - » Composition
  - » Communication
- Code Generation
  - » CSPm
  - » CTC++
  - » occam
- Prototype

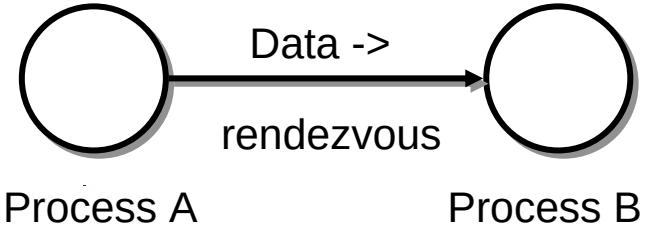


CT-library: CSP-based Software Framework

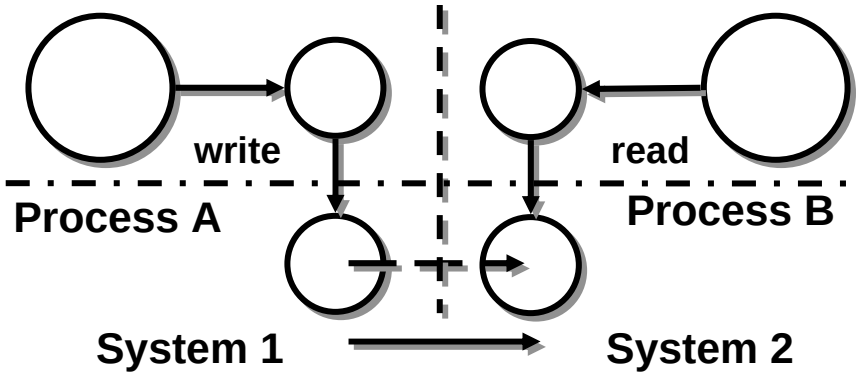
- **CSP Process**
  - **Active object: One thread of control**
- **CTC++ software library**
  - **Implements as building block-components**
  - **Connections as channels (synchronous, rendezvous)**
    - » **Link Drivers**
  - **Scheduler included (kernel-like)**
  - **Runs on Windows, DOS, RTAI (linux), ADSP**



  - **Prototype**



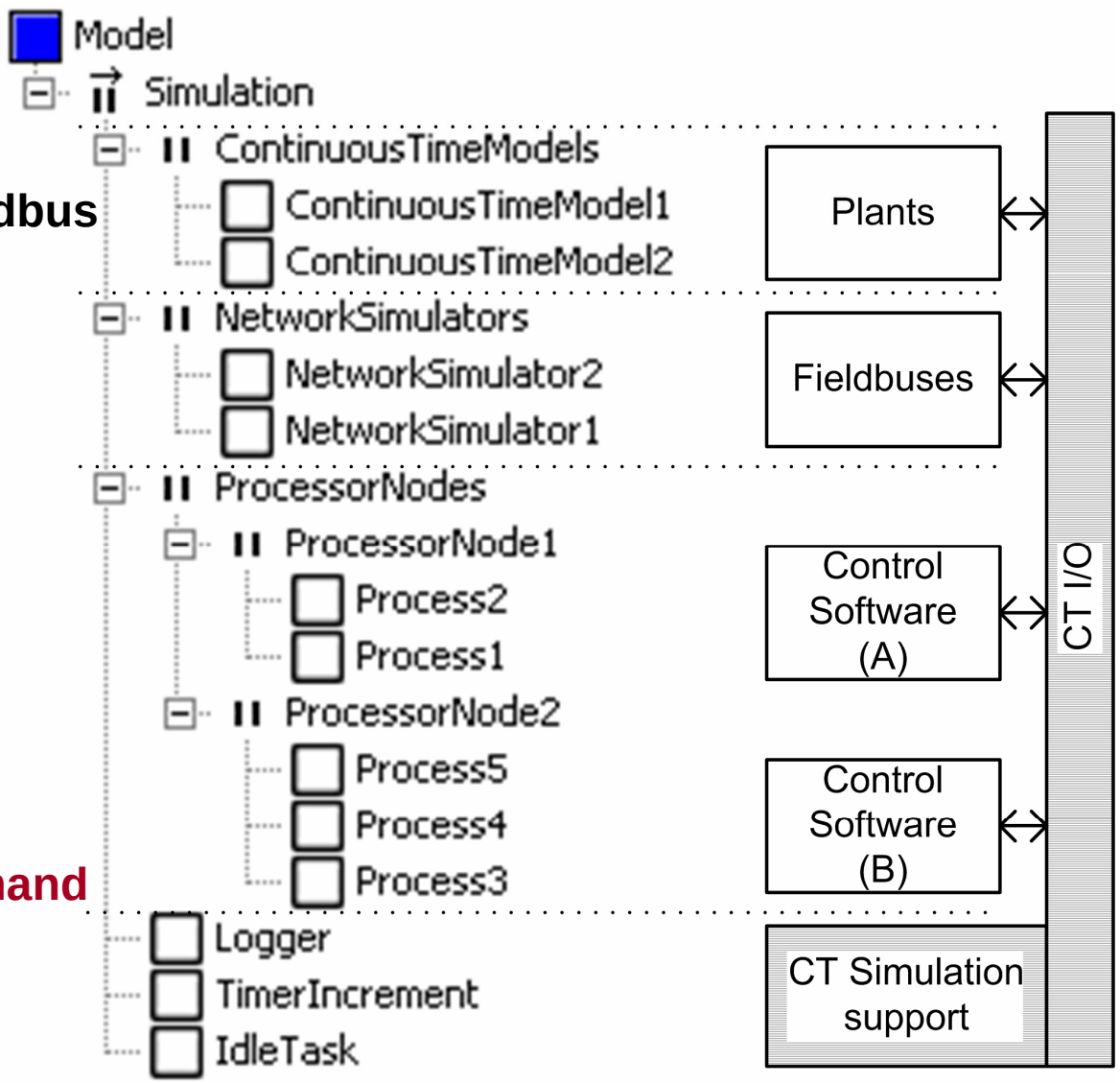
Data-flow model



distributed / heterogeneous

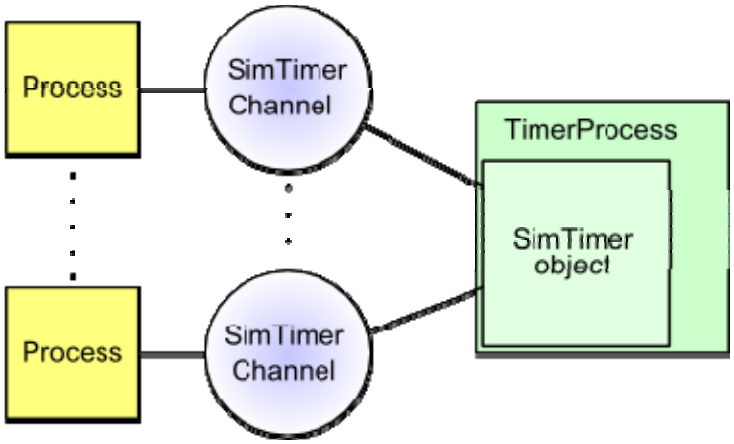
NWsim: Distributed Simulation Framework

- **CSP approach**
  - All parts are CT processes
  - Remote Channels couple to Fieldbus
  - Network Simulator based on TrueTime
- **Time Synchronization**
  - Prioritized Parallel
  - Rendezvous in Timer Channels
  - SimTimer advances time
- **Interaction continuous – discrete parts**
  - Basic integration methods (continuous part)
  - Plant model calculations on demand
  - 1st try out



Details / Limitations

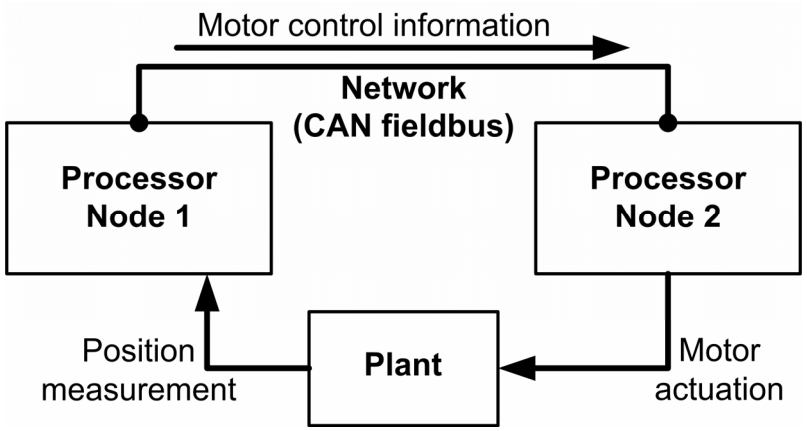
- **Assumptions**
  - Software execution time ignored
  - Execution should be fast compared to communication
- **Adaptations to TrueTime**
  - Change of environment
    - » CT Process, Interface with Timer,
    - » Remote Channel driver
  - Functionality
    - » Node numbering and checking
    - » Input queue sorting on priority

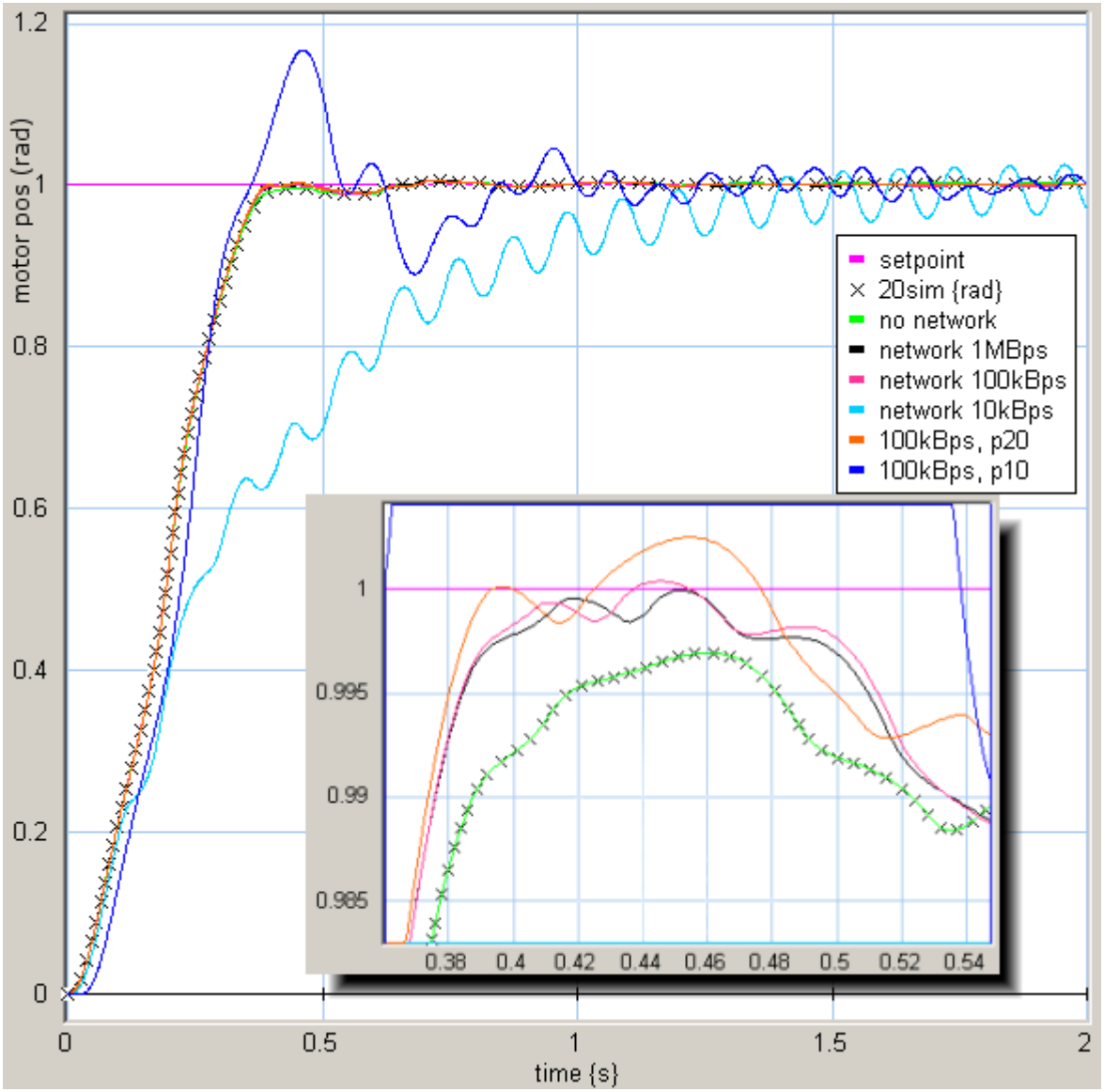


- **Towards real-time**
  - NDD of Remote channel & SimTimer -> Real versions

Network Simulator - Case

- **Simulator OK**
  - **compared with traditional**
- **Network parameters**
  - **Influence behavior**
  - **Optimal via simulation**

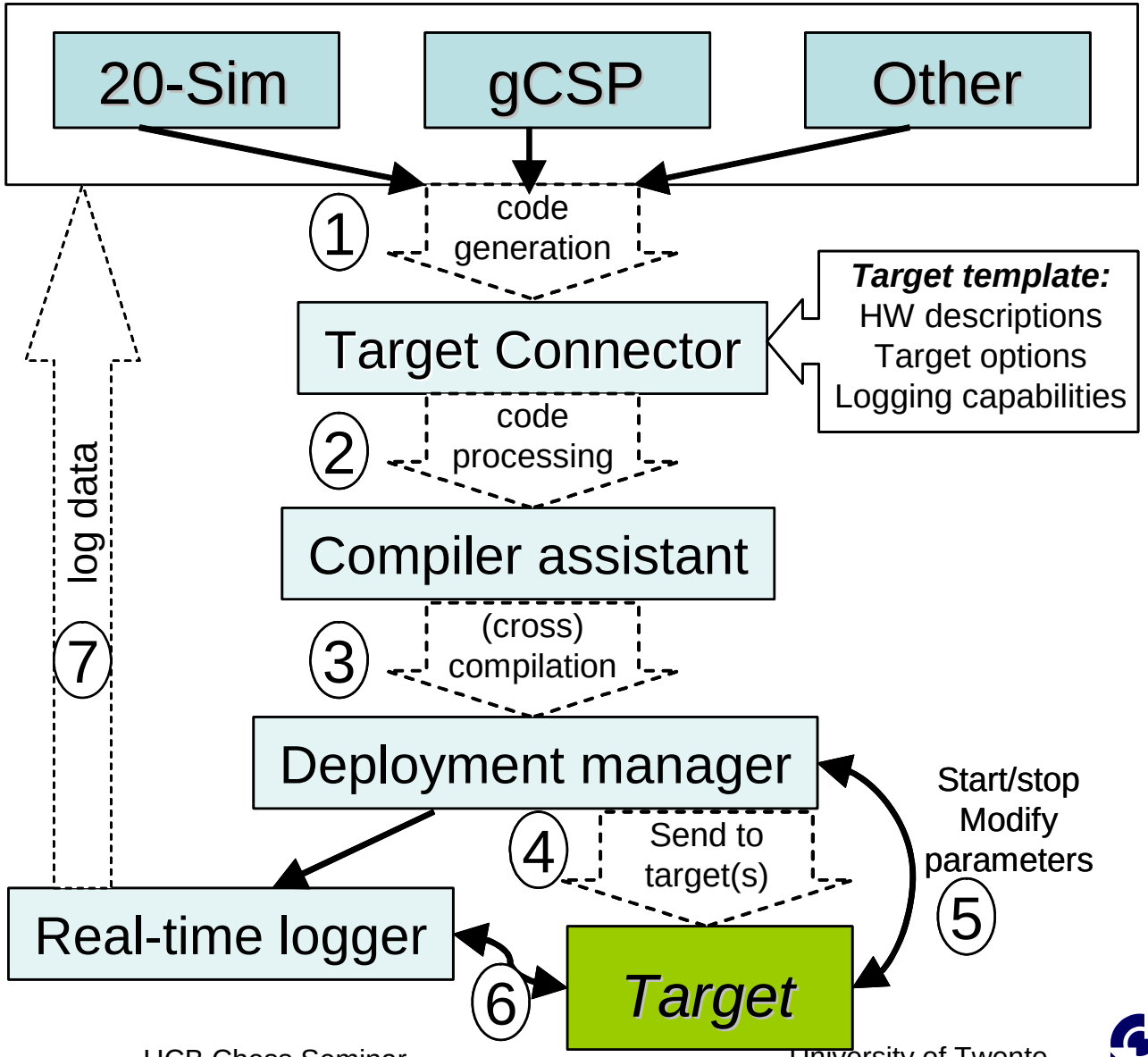




ForSee: Connect, Compile, Configure, Command

Code -> Target

- Connect
  - » Model variables to target signals
    - Token replacement
  - » Keeps model free of target anomalies
- Guides
  - » Compilation, Configuration, Logging specification
- Prototype



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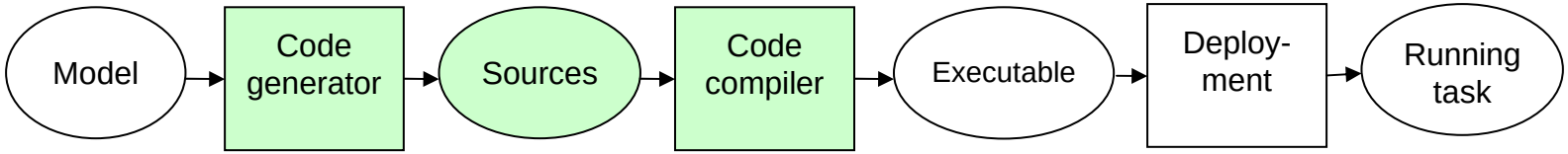

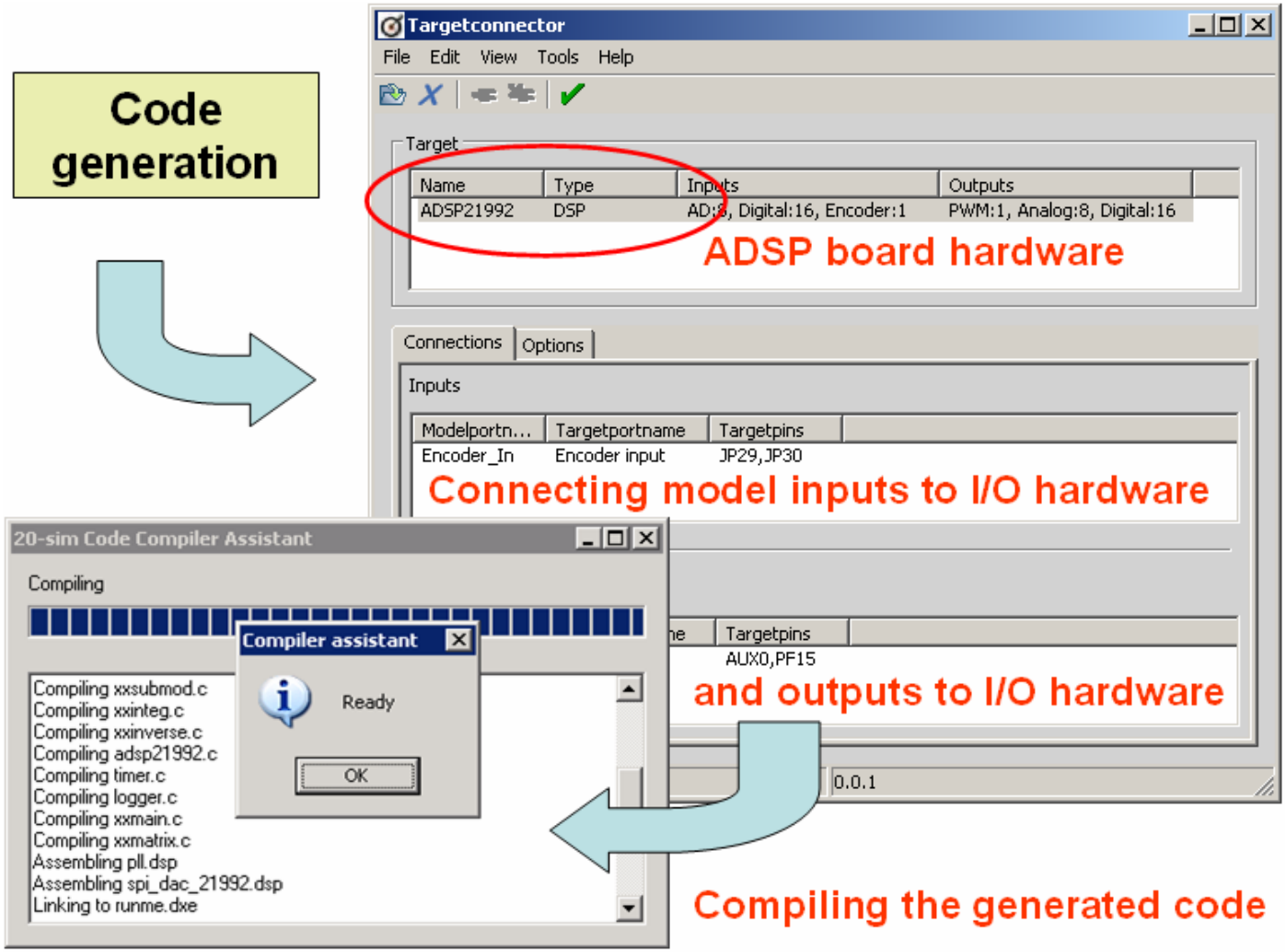

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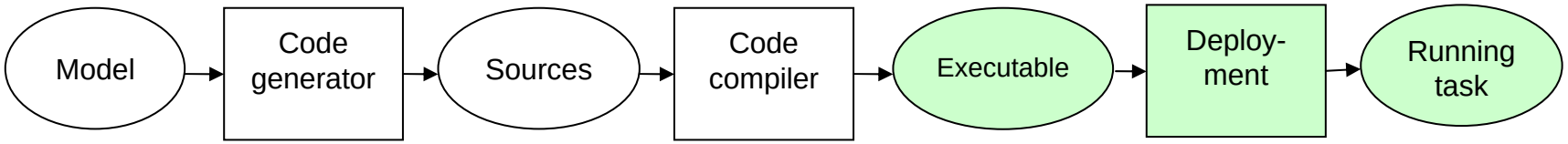
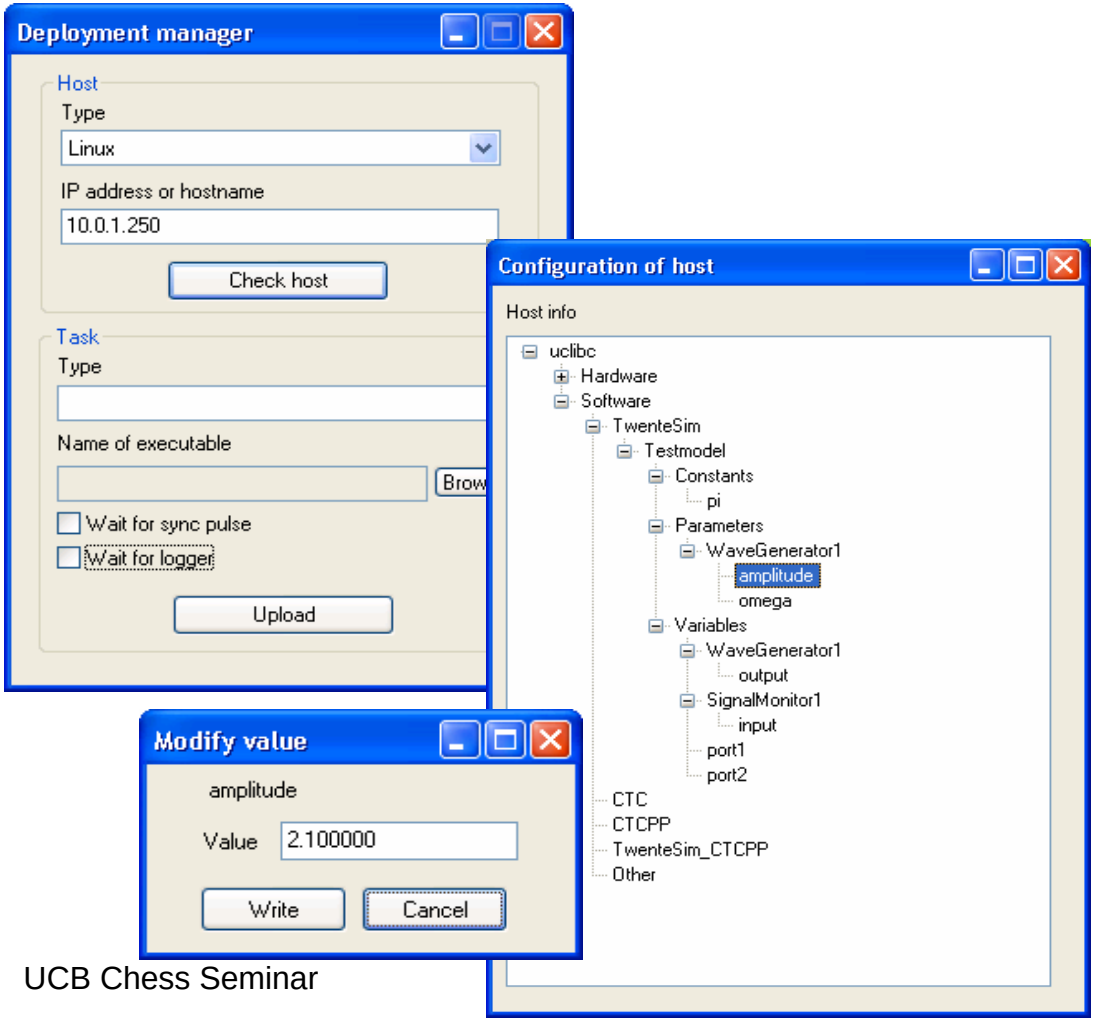


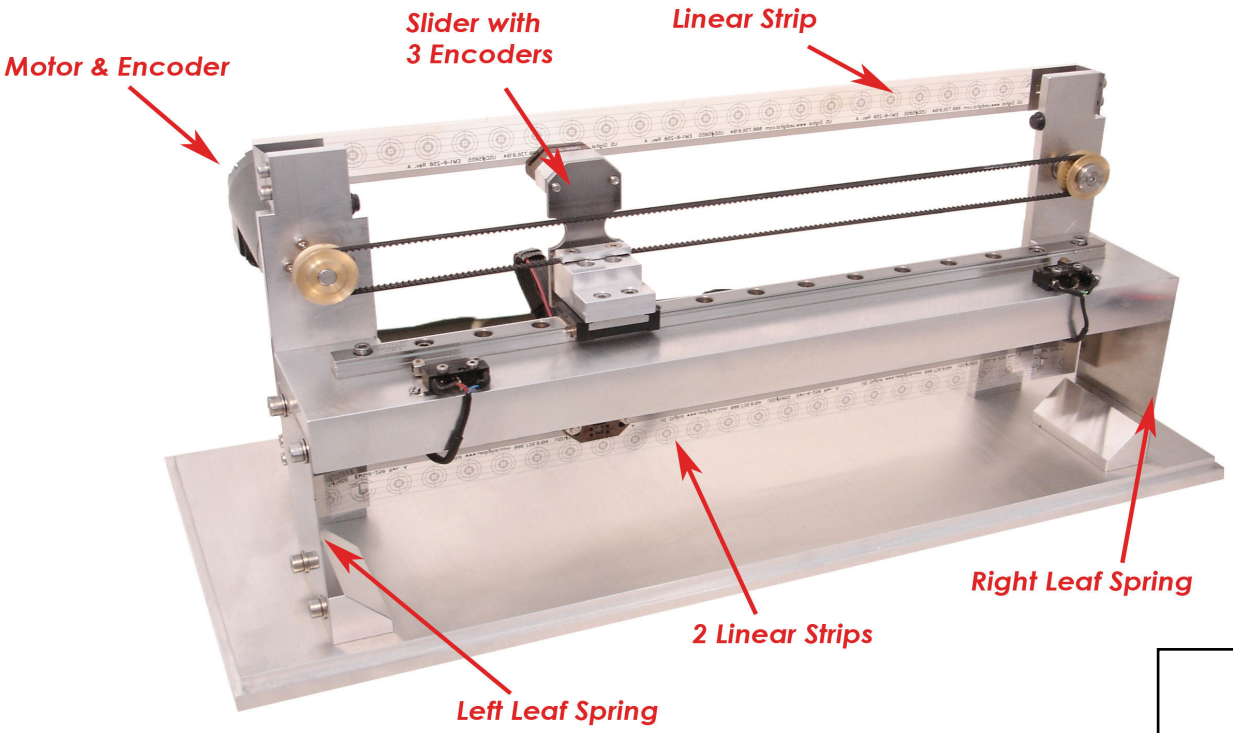
Deployment manager

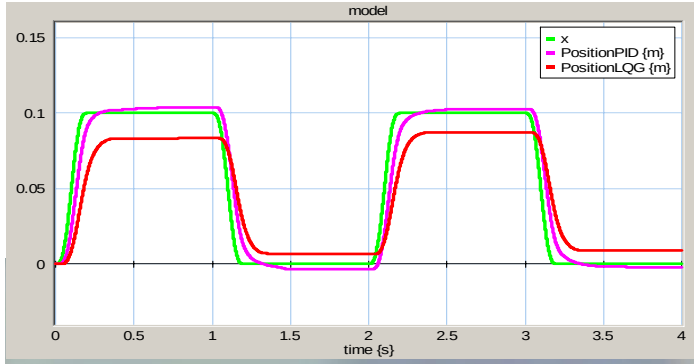
- Check target (status)
- Upload
  - » Executable
  - » Configuration (parameters/hardware)
- Task control
  - » Start/Stop
  - » Data logging control
- Retrieve log data
- Modify/inspect parameters

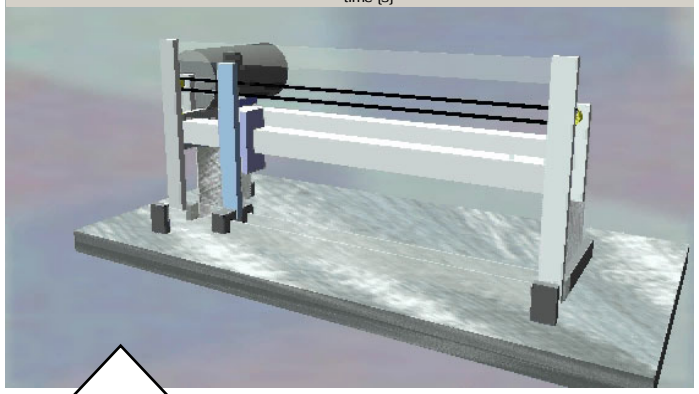


ForSee: Connect, Compile, Configure, Control

- Real-time logging
- Work in progress





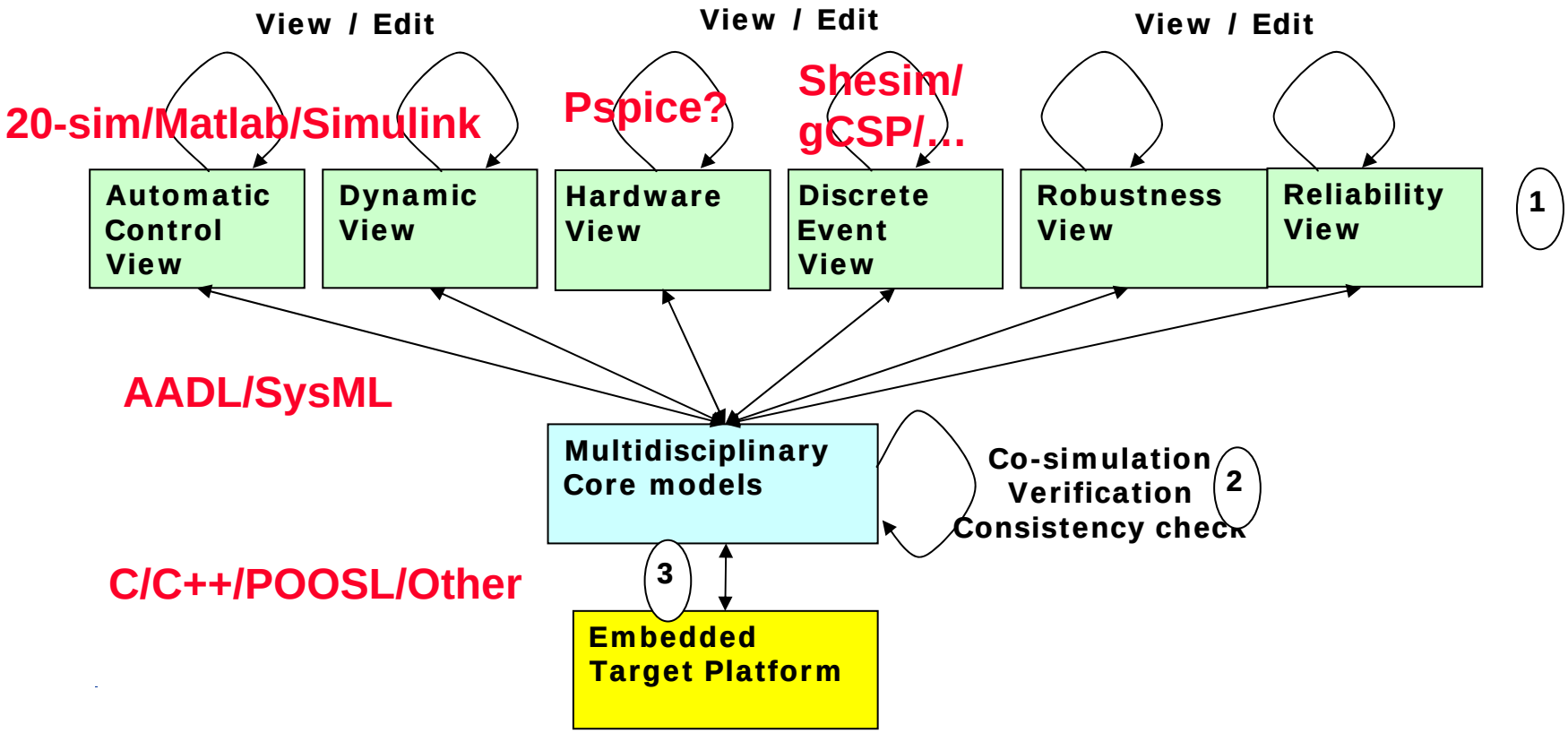


3D model follows real setup

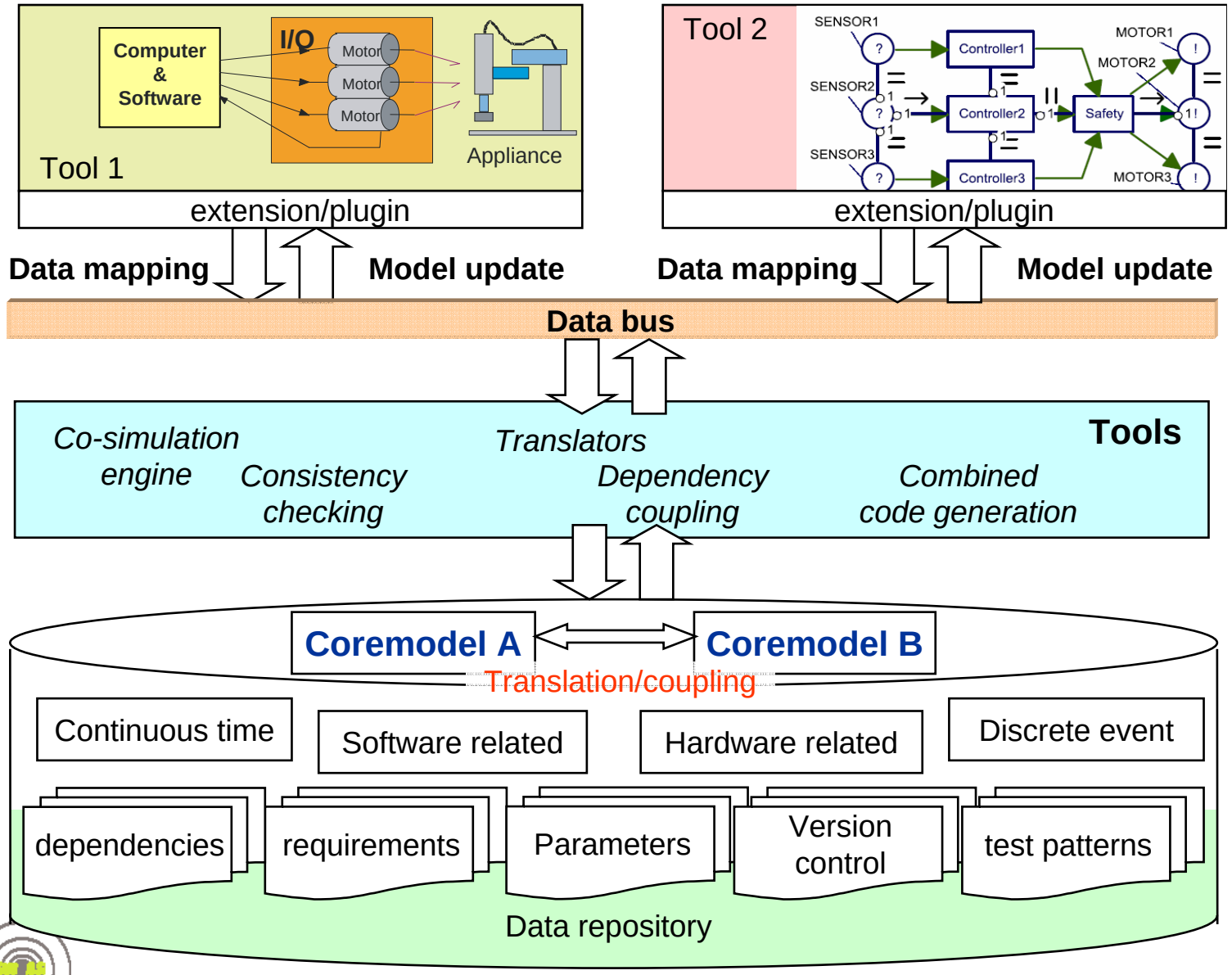
Further tool integration

- **Current tools cover design flow**
  - **Cooperate smoothly**
  - **Still separated per discipline**
- **Real cooperative design**
  - **One-model – One-tool approach not feasible**
    - » **Multiple view modeling (& tools)**
  - **Tightly coupling needed also on model level**
    - » **Check cross-domain aspect relations**
  - **Co-simulation on execution level**

Design methodology



Multi-view Integration Framework



Tools, viewpoints & views

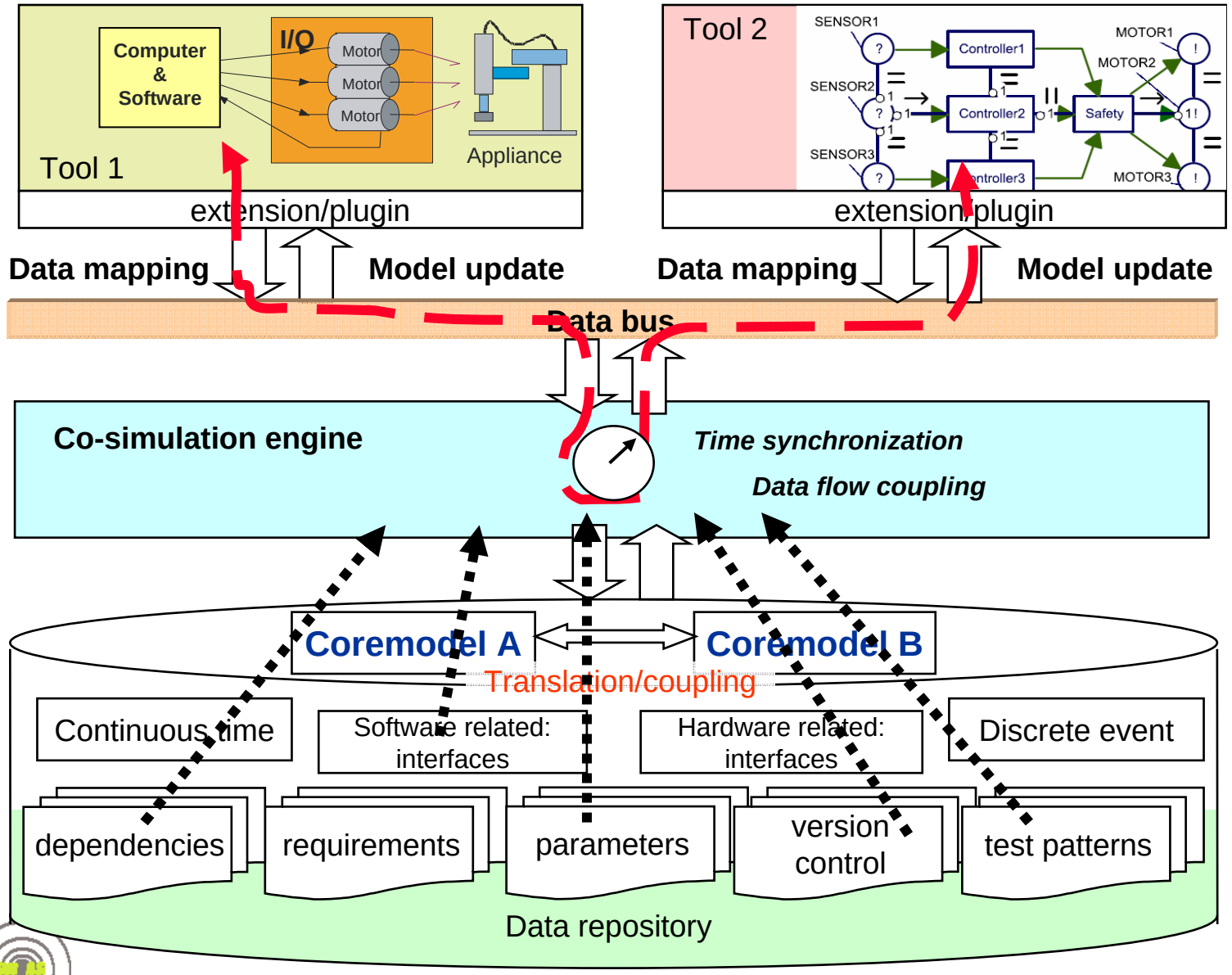
Data exchange

Tool integration layer

Tool neutral format: core model

Inter-view Data storage

Example: Co-Simulation



Tools, viewpoints & views

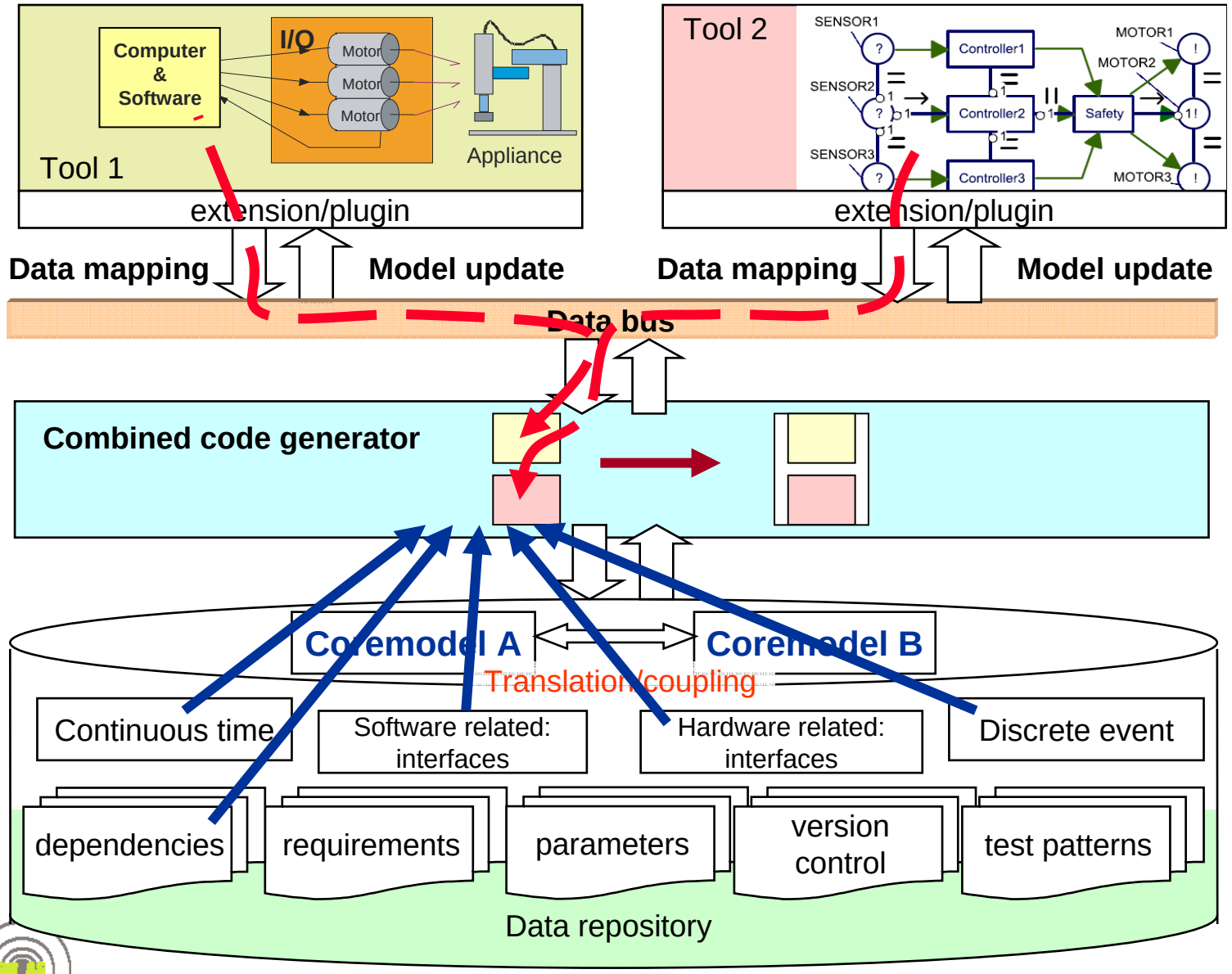
Data exchange

Tool integration layer

Tool neutral format: core model

Inter-view Data storage

Example: Code Generation



Tools, viewpoints & views

Data exchange

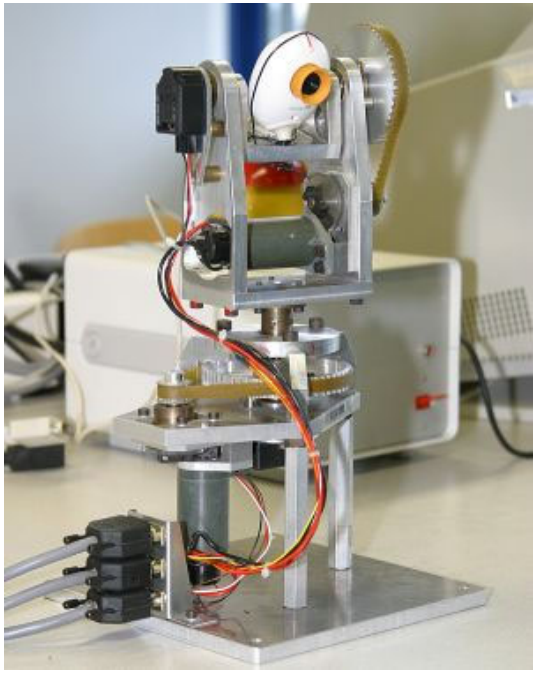
Tool integration layer

Tool neutral format: core model

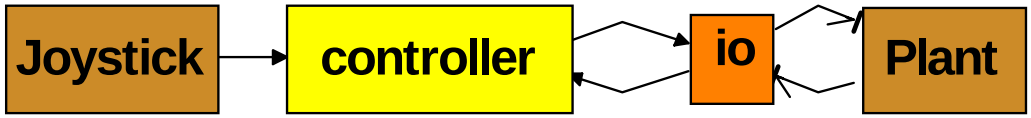
Inter-view Data storage

Case: twin-axes device JIWY

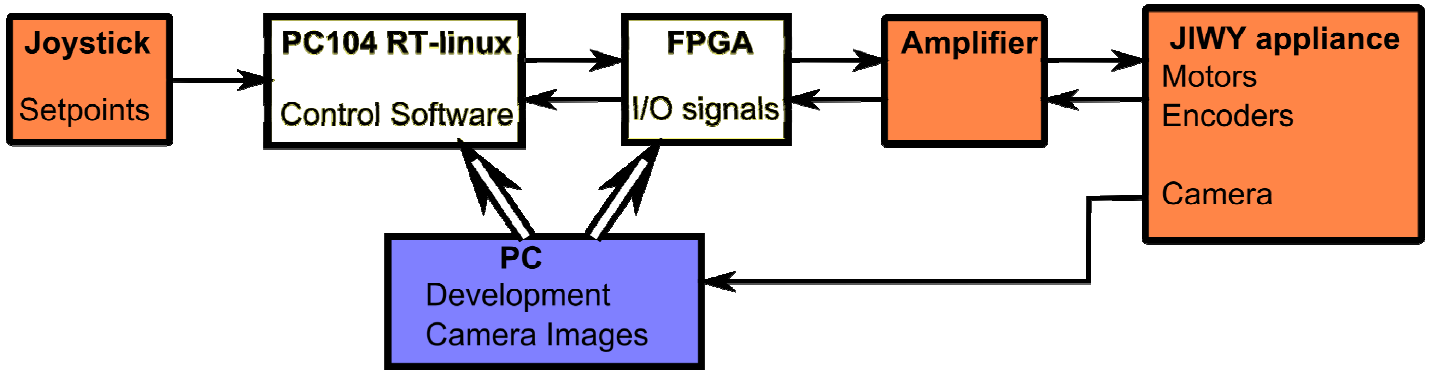
- **Characteristics**
  - 2 motor encoder pairs
  - Timed belt driven



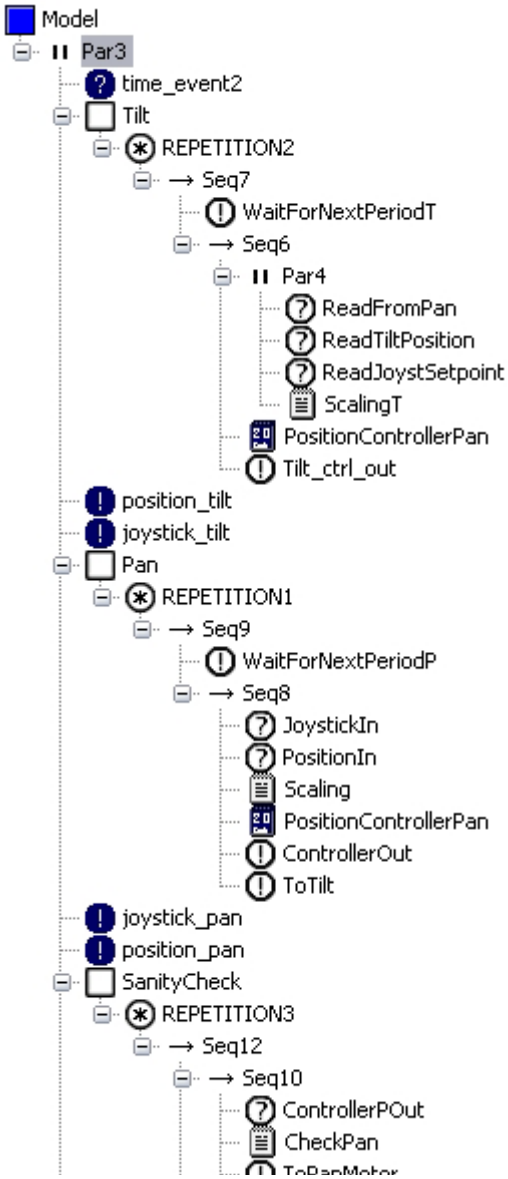
Toplevel model (step 1 & 2)

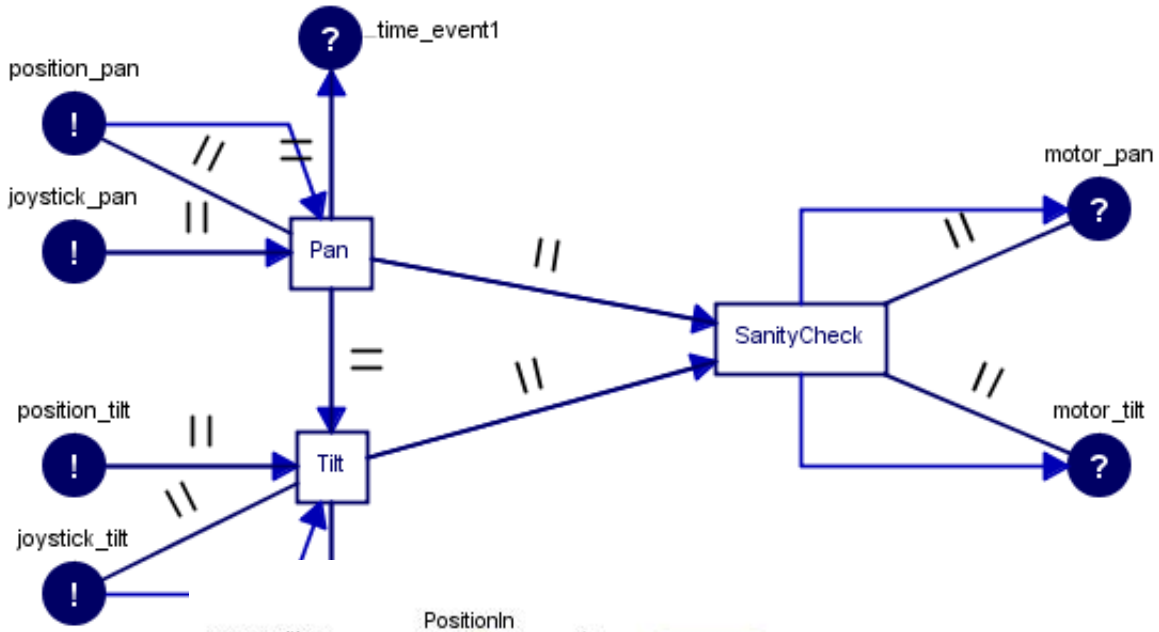


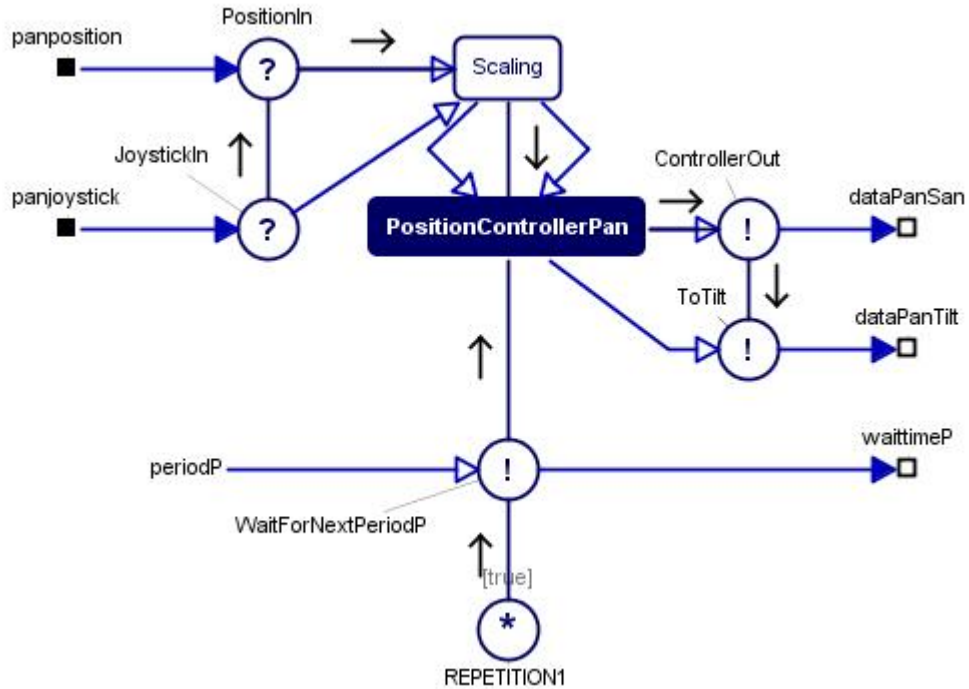
Configuration



JIWY: SW models







Cases: Observations

- **JIWY & Tools**
  - **4th Yr EE elective course on Real-Time Software**
    - » **Preparation exercises to follow the workflow**
    - » **"Doing right first time" on real setup succeeded**
- **Tools**
  - **Shorting of design time observed**
  - **2nd Yr EE students, mechatronics project**
    - » **ECS completely hidden (only 20-sim, 4C)**
  - **MSc projects**
    - » **Robotics / Mechatronics: effective use**
    - » **ECS: stress testing parts of the chain**

Conclusions

- **Prototype tool chain functions rather smoothly**
- **Shortening design time not (yet) significant**

- **Continue working on the tools**
- **Use larger cases in cooperation with Industry**