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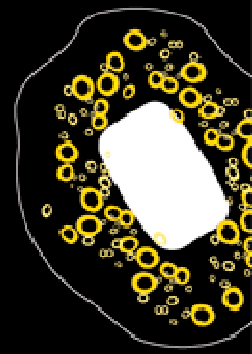

Concurrent Design of Embedded Control Software

Third International Workshop on Multi-Paradigm Modeling
MPM`09, 06-10-2009

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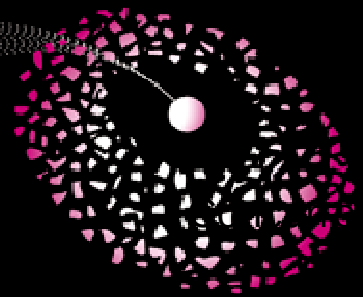


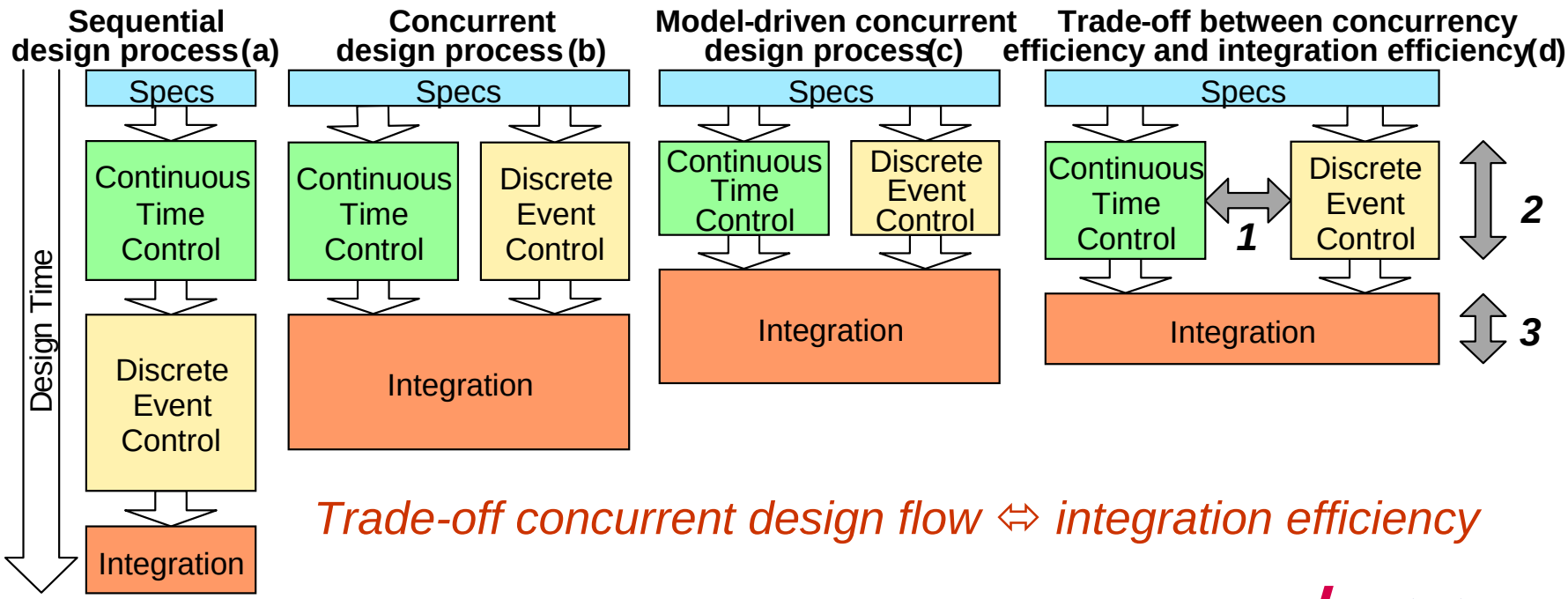
Contents

- Introduction
  - Mechatronic systems design challenges
  - Embedded Control Systems software
- Model-driven Design Methodology
- Case study
- Results & Conclusions

Introduction – Mechatronics challenges

- Developing Reliable and Robust Embedded Control Software for mechatronic applications is too costly and too time consuming.

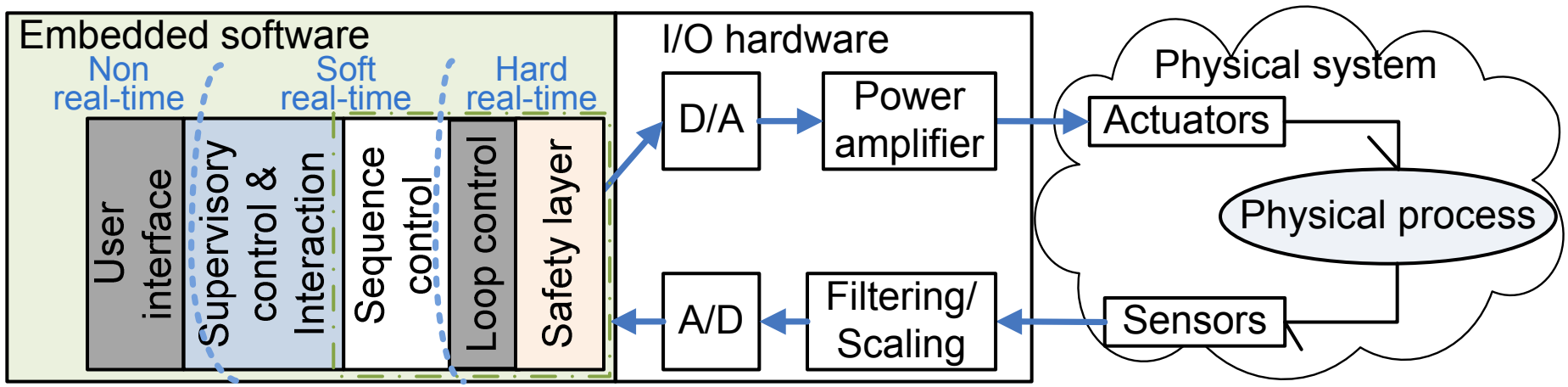
- Reasons:
  - Complexity, Heterogeneity, Lack of Predictability, Late Integration
- Approaches to tackle the problem
  - Concurrent Engineering, Model Driven Design, Early Integration



Trade-off concurrent design flow ⇔ integration efficiency

Mechatronics: Embedded Control Systems

- Essential Properties Embedded Control Software
  - Dynamic behavior of the physical system essential for SW
  - Real-time constraints with low-latency requirement
  - Dependability: Safety, Reliability
- Layered Software structure



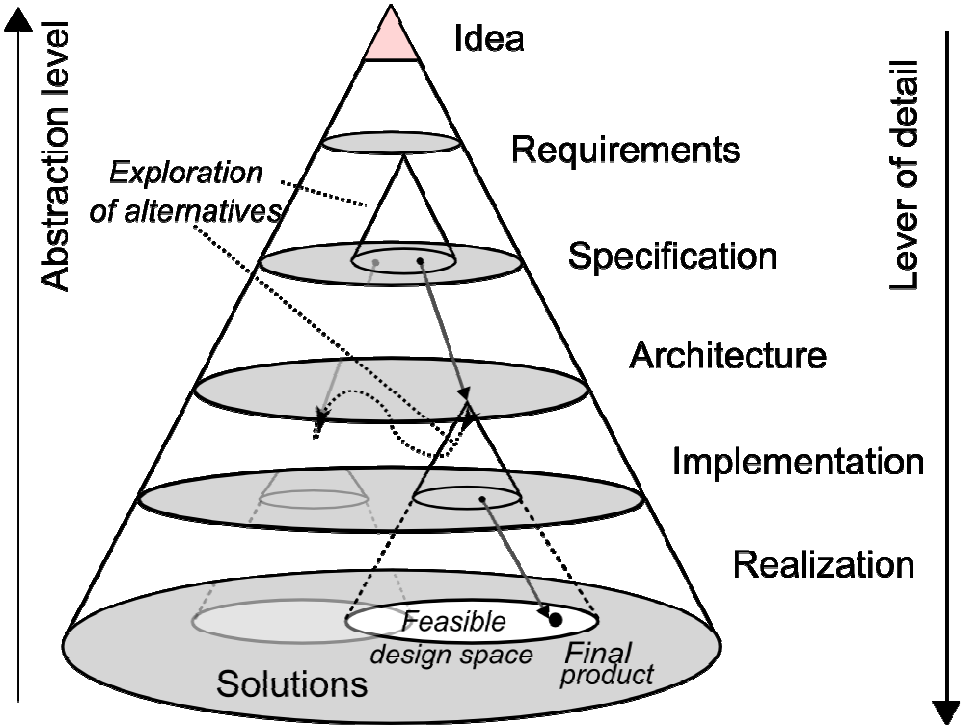
- Model-driven Design
  - Heterogeneous modeling
  - Multiple Models of Computation
  - Multiple Modeling formalisms

ECS Design Methodology

- Aim
  - Efficient Concurrent Design
  - Fast Integration
  - Reliable Result
- Approach:
  - Model-Driven Design
  - Concurrent Design
  - Code Synthesis

ECS Design Methodology

- Way of Working
  - Abstraction
    - Hierarchy
      - Split into subsystems
      - Cope with complexity
  - Model-driven design
    - Design Space Exploration
      - Aspect models
      - Make choices
      - Limit solution space
    - Step-wise refinement
      - Add detail
      - Lower abstraction
    - Implementation
    - Realization
  - Concurrent design trajectory
    - Mechanics, Electronics, SW: Discrete Event, Continuous Time
  - Model-level Early Integration where needed



Design Methodology Discrete Event

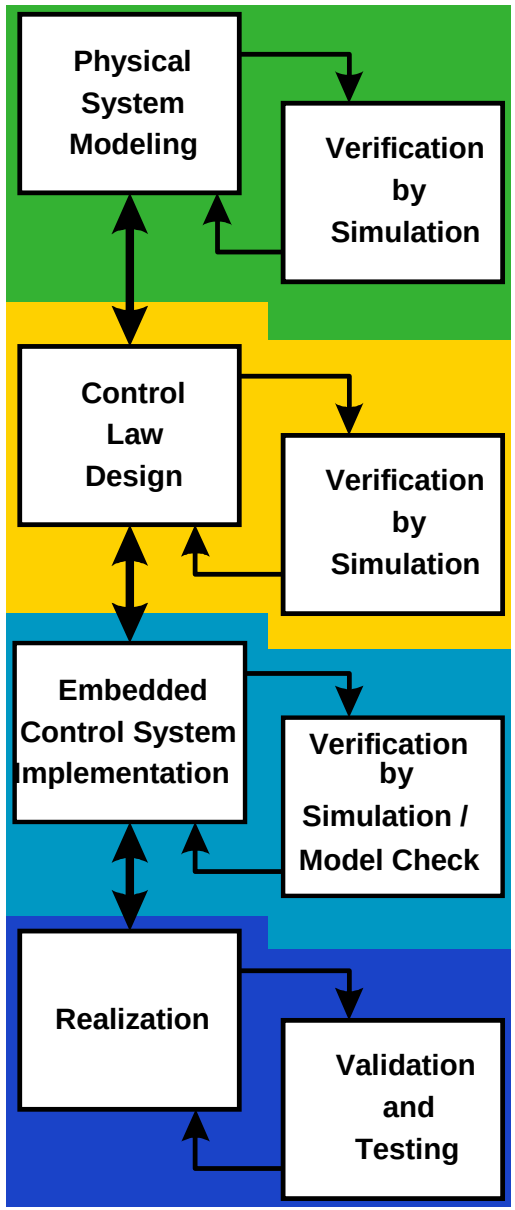
- Approach
  - Stepwise & local refinement
  - Verification by simulation & model checking
- Way of working
  - System partitioning into concurrent actors
  - C-model : Abstract interactions between concurrent actors
  - M-model : Interaction between different MoCs
  - R-model : Timing low-level behavior
  - Property preserving code synthesis

Characteristics	*Models*	*Abstraction level*
Concurrency	C-model	High ↓ Low
Multi MoC	M-model	
Real-time	R-model	

Design Methodology Continuous Time

- Approach
  - Stepwise & local refinement
    - From model towards controller code
  - Verification by simulation

- Way of Working
  - Model & Understand
    - Physical system dynamics
  - Simplify model, derive the control laws
  - Interfaces & target
    - Add non-ideal components (AD, DA, PC)
  - Dependability: Safety, Reliability, …
  - Integrate control laws into ES
    - Scaling/conversion factors
    - Via local refinement:
      - {Software/Processor/Hardware}-In the Loop



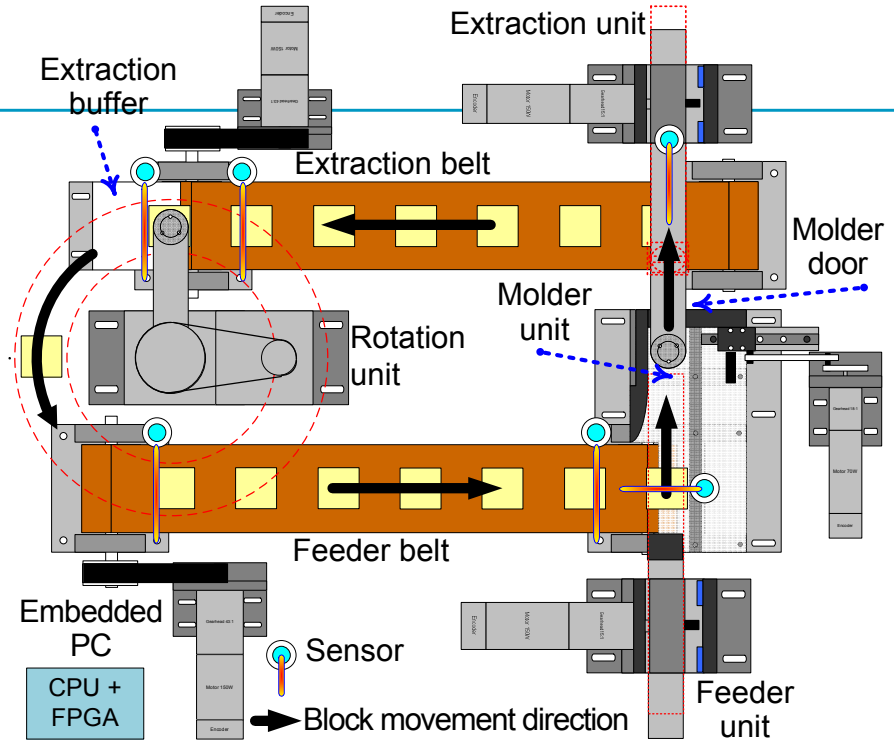
Case study Overview

- Goals
  - Apply our methodology
    - Real-world setup with industrial complexity
    - Concurrent model-driven design
    - Trade-off integrated design flow ⇔ partial separated design flow
  - Integration efficiency analysis
    - Comparison with other test cases on the same setup

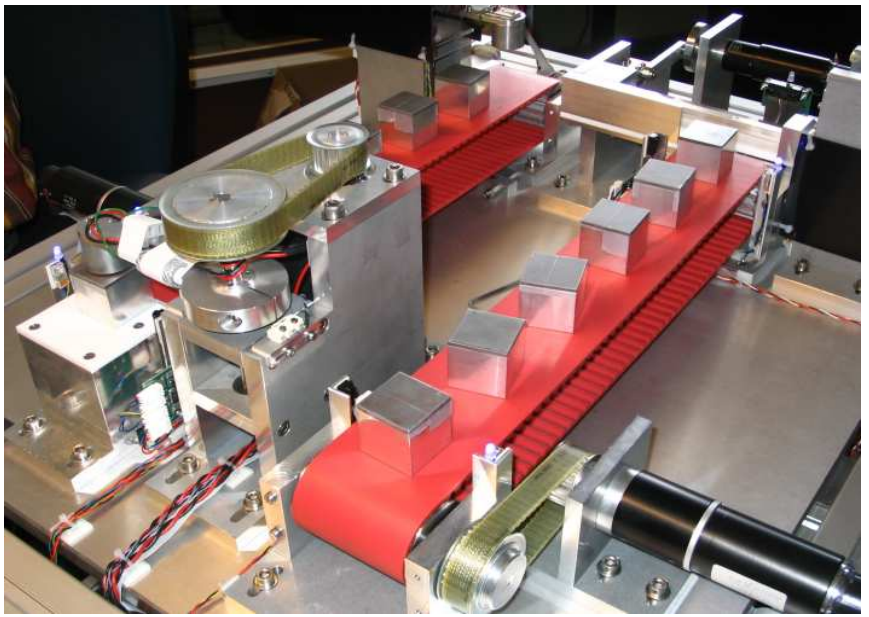
Case Study Production cell

Production cell demonstrator

- Based on:
  - Stork Plastics Molding machine

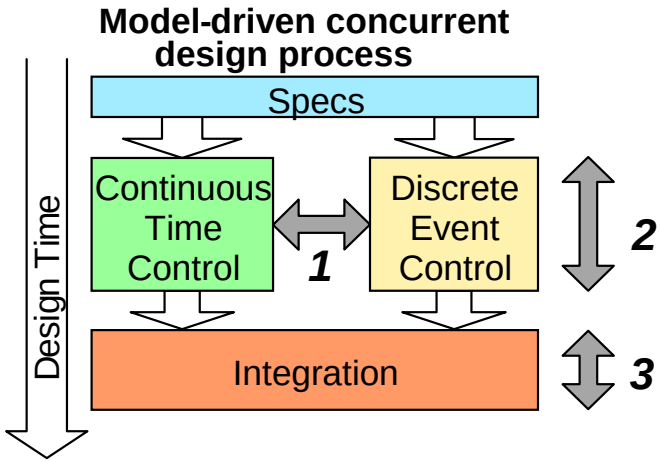


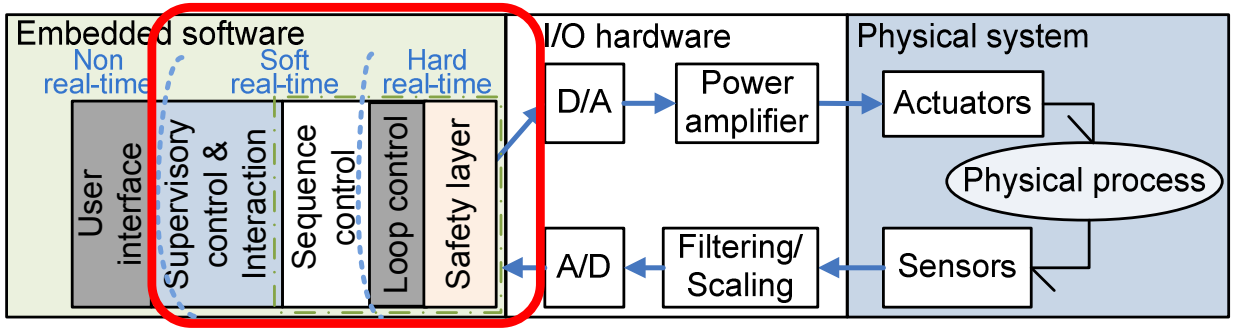
- Architecture
  - CPU (ECS) + FPGA (digital I/O)
  - Distributed Control possible
- 6 Production Cell units
  - Action in the production process
    - Molding, Extraction, Transportation, Storage
  - Synchronize with neighbors
  - Deadlock possible on > 7 blocks



Case Study Production cell

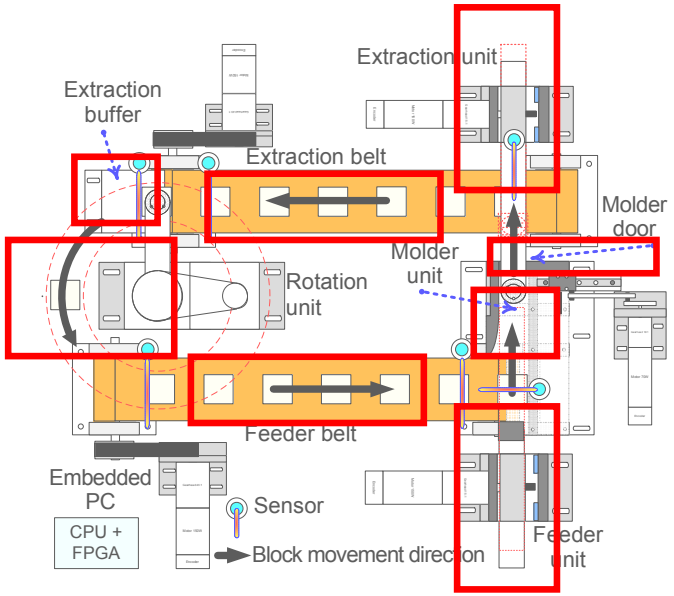
- Embedded Control System Software Design
  - Jointly
    - Specs, partitioning, interfaces
  - Concurrently
    - SW partitions
  - Jointly
    - SW integration & testing

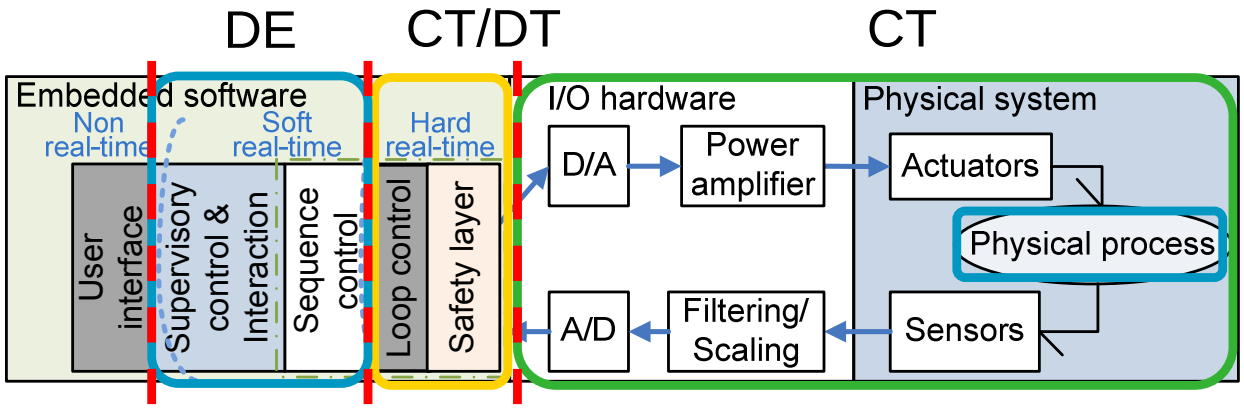




Case Study Partitioning & Hierarchy

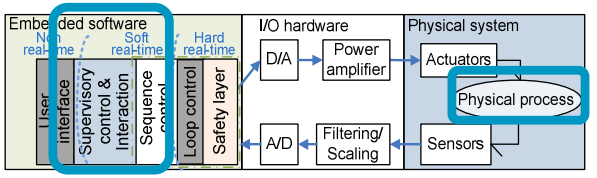
- Embedded Software
  - Discrete Event partition
  - Continuous/Discrete Time partition
- Based on
  - Top level system model
  - Production Cell Units (PCUs)
  - Layered Software structure
  - Interface



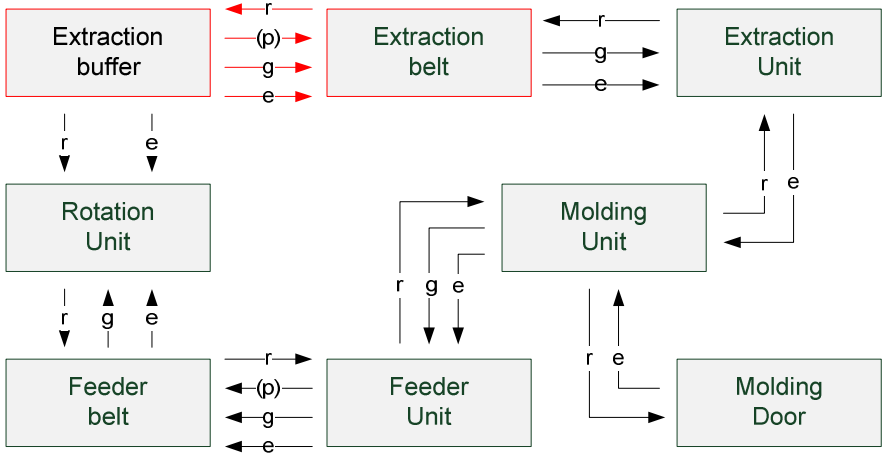


Interface definitions

Discrete Event Software Design



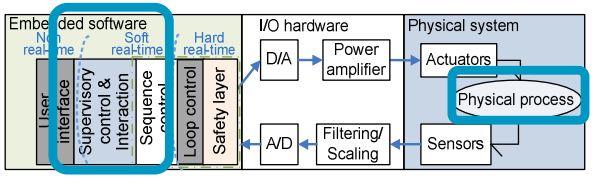
- Modeling tools : SHESim/Rotalumis
  - POOSL: Parallel Object-Oriented Specification Language
  - SHESim: Graphical tool for model construction and simulation
  - Rotalumis: Fast execution engine built in C++
- C-model : handshake diagram formalized in POOSL model
  - Partitions design into a set of concurrent actors
  - Actors synchronize action by a handshake sequence
  - Models untimed abstract interactions between actors



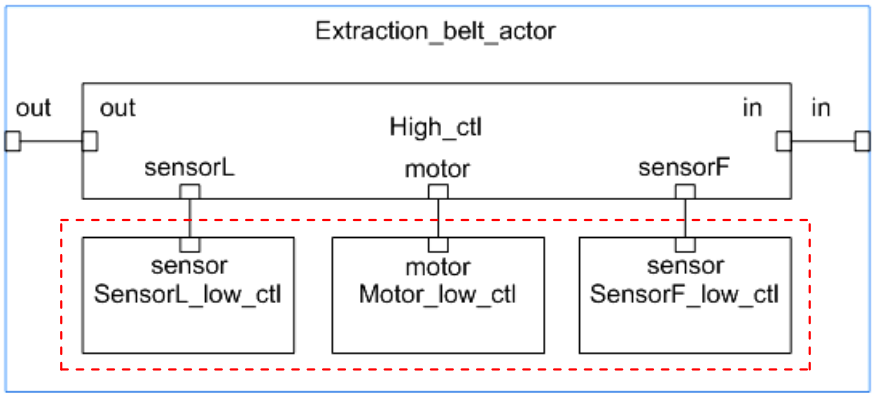

```
To_Extraction_buffer()()
 [last] out! request;
 sel
        out? grant{blocked:=false}
 or
        out? postpone{blocked:=true};
        out? grant{blocked:=false}
 les;
        { last:=false; load:=load-1 };
        out! end;
To_Extraction_buffer()().
```

```
From_Extraction_belt()()
 in ? request;
 sel
        [empty] in! grant
 or
        [empty=false] in! postpone;
        [empty] in ! grant
 les;
        in? end {empty:=false};
From_Extraction_belt()().
```

Discrete Event Software Design



- M-model:
  - Refinement of C-model
  - Adds interfaces to low-level behavior
  - Focuses on interactions between high-level DE-control and DT/CT loop control (MoC interaction)
  - Externally observable behavior is kept the same

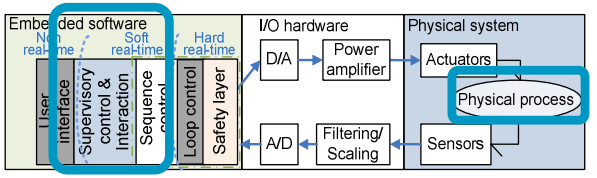



```
To_Extraction_buffer()()
[last] out ! request;
sel
  out ? grant{ blocked:=false }
or
  out ? postpone{ blocked:=true };
  motor ! stop;
  out ? grant{ blocked:=false };
  motor ! start
les;
sensorL? off{ last:=false; load:=load-1 };
out ! end;
To_Extraction_buffer()().
```

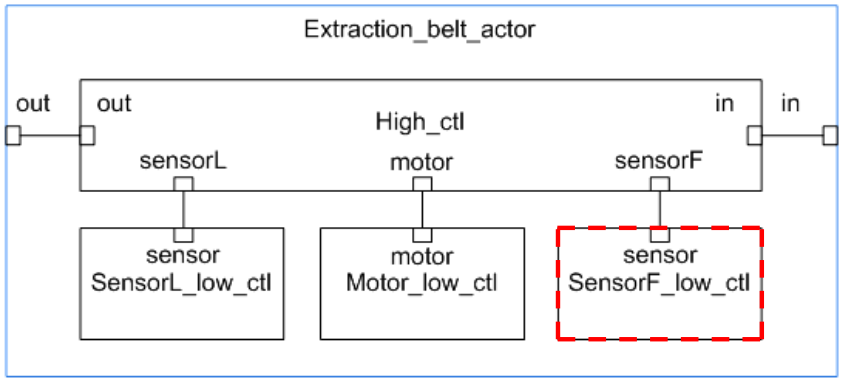
```
Discrete_Sensor()()
sel
  sensor ! on
or
  sensor ! off
les;
Discrete_Sensor()()
```

```
Discrete_Motor()()
  motor ? start;
  motor ? stop;
Discrete_Motor()()
```

Discrete Event Software Design



- R-model:
  - Refinement of M-model
  - Adds low-level behavior
  - Both DT and DE behavior
  - Adds timing
  - Again, externally observable functional behavior is kept the same

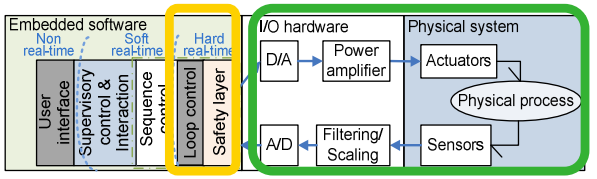


- Automatic code synthesis:
  - Automatic mapping to target platform
  - Property-preserving code generation
  - Building blocks with common interface
  - Mathematically proven timing relation between model and implementation

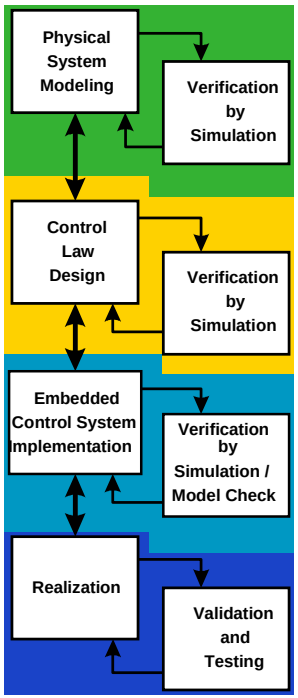
```
Discrete()()
 sel
   [ (curstate) & (prestate=false) ]
          sensor ! on { prestate := curstate }
 or
   [ (prestate) & (curstate=false) ]
          sensor ! off  { prestate := curstate }
 les;
Discrete()().
```

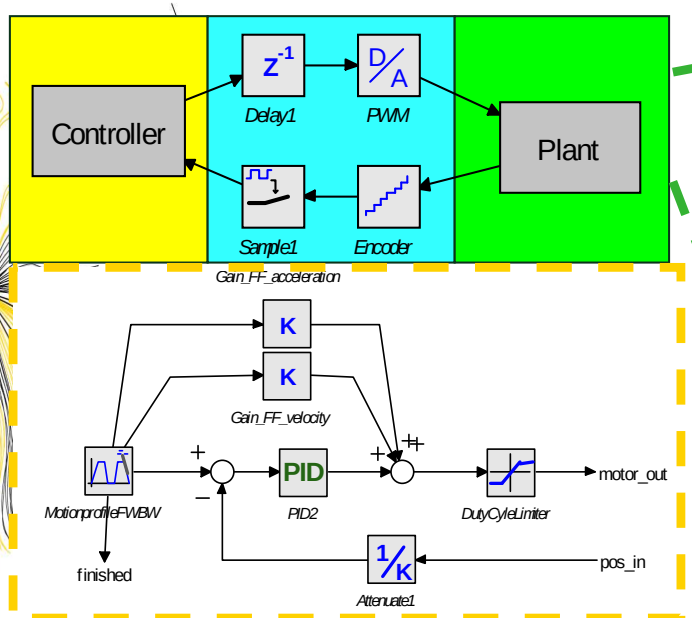
```
Continuous()()
   [ curstate = prestate ]
       curstate := sensor Read;
   delay 0.01;
Continuous()().
```

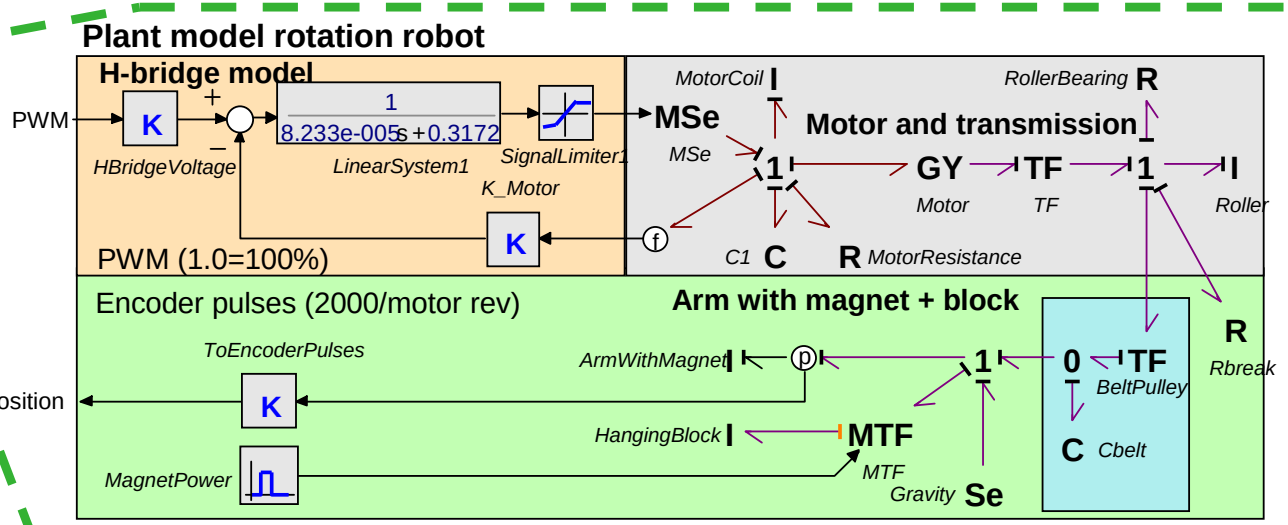
Continuous Time Software Design



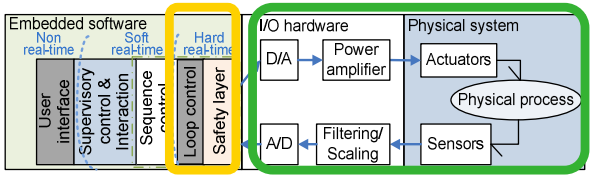
- Goal
  - Loop Controller Algorithm in C++ POOSL dataclass
  - Low Level Safety & Sanity Check
  - Event Interface (start/stop/error …)
- Modeling Tools & Languages: 20-sim
  - Physical System Model: ODE, bond graphs, data flow
  - Code Synthesis: template based C/C++

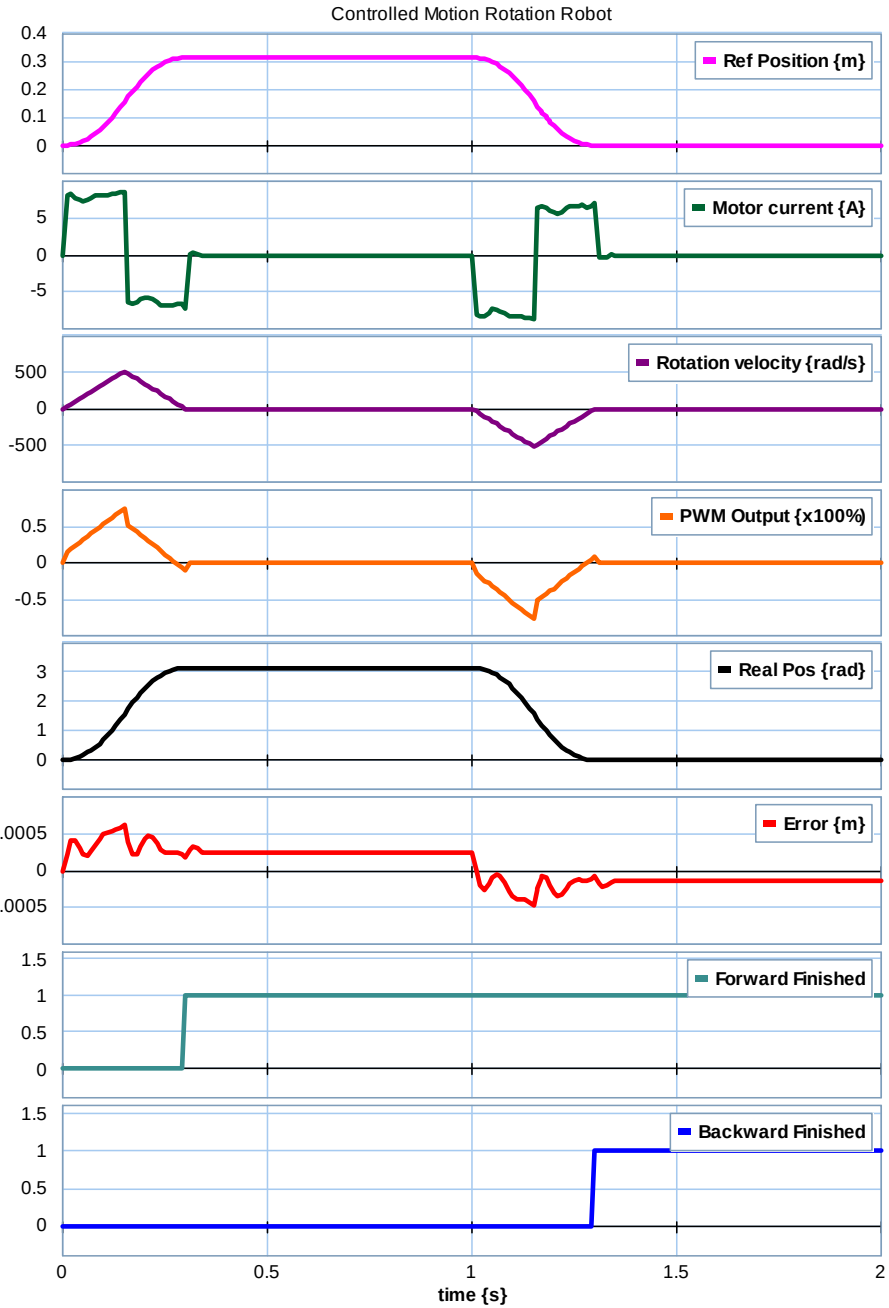


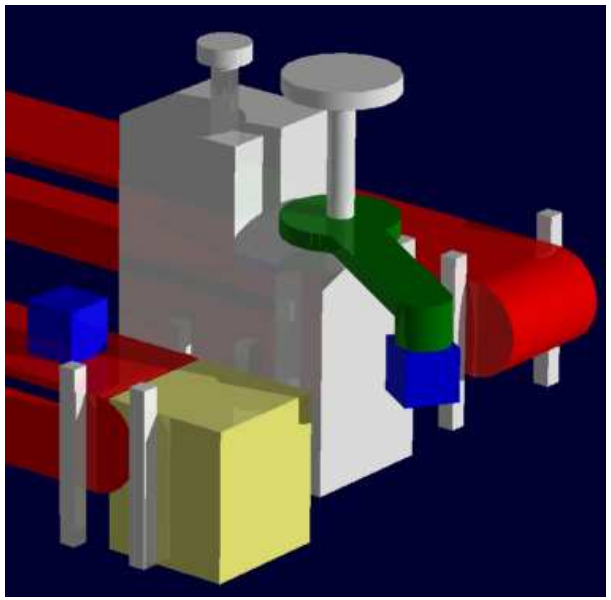


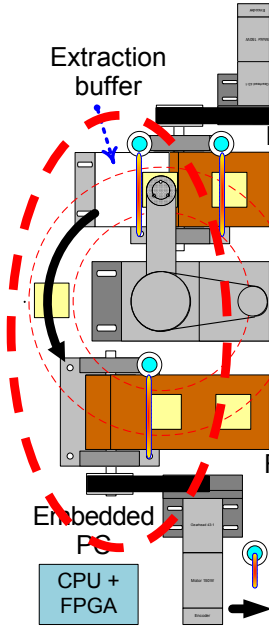


Continuous Time Software Design





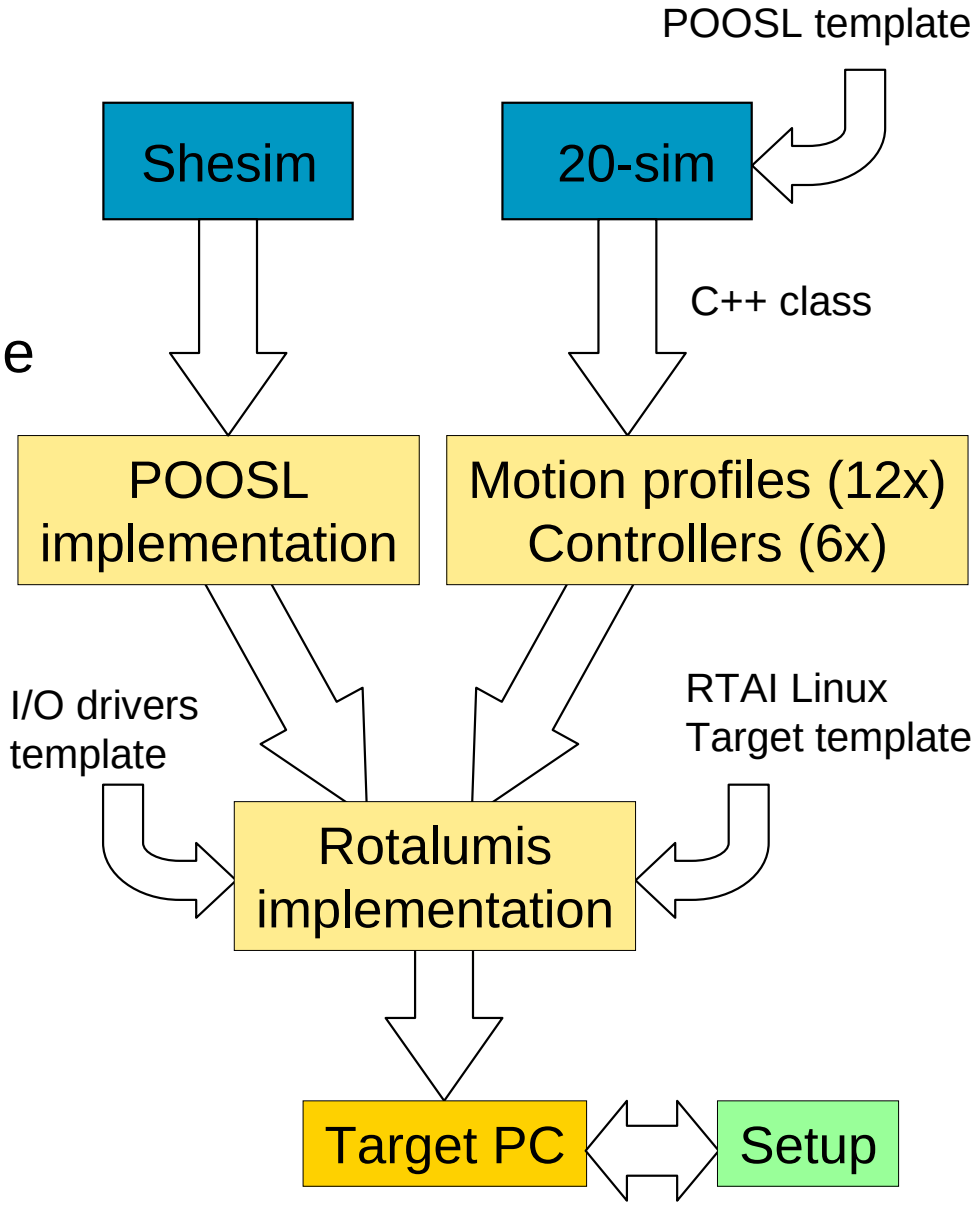





```
class Controller_Rotation: public PooslDataClass
{   /* the model functions */
    void Initialize (double *u, double *y, double time);
    void Read (double *u, double *y);
    void Calculate (double *u, double *y, double time );
    void Write (double *u, double *y);
    void Terminate (double *u, double *y);
};
```

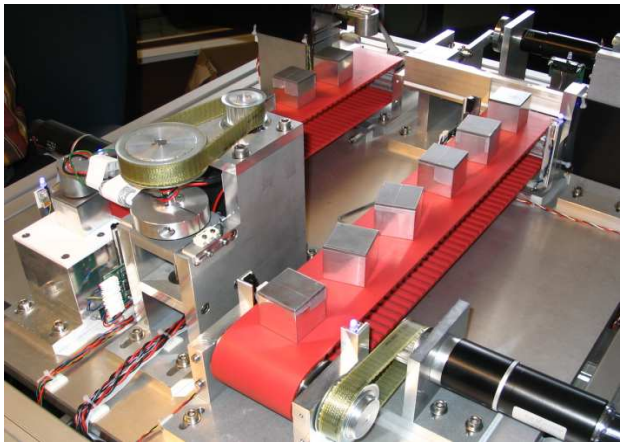
Integration

- Discrete Event
  - Last iteration:
    - Timing
- Continuous Time / Discrete Time
  - Last iteration:
    - Event interface
    - Target unit test
- Code synthesis
  - Stepwise
  - Partial code generation
  - Template based
  - Simulation feedback
- Target tests

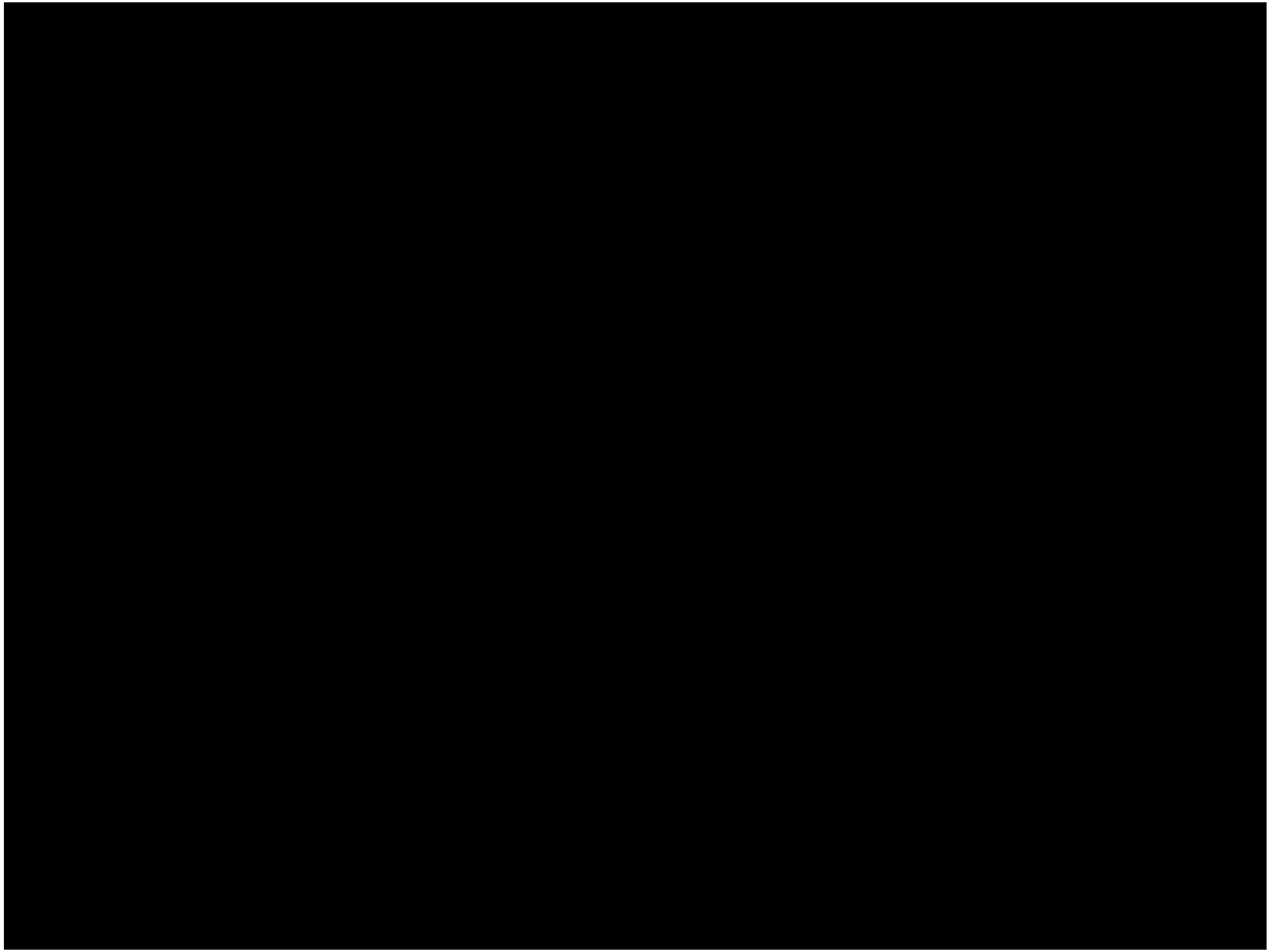


Results & Discussion

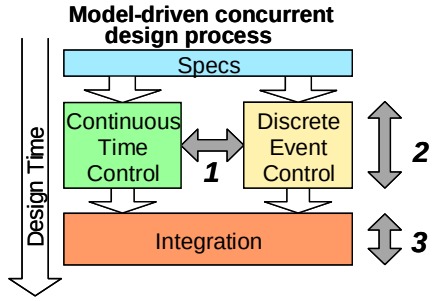
- Short integration & testing phase
  - < 2 days, previous case: > week
- Almost running first time right
  - Minor timing issue with magnet on/off traction delay
- Concurrent, but separated design
  - Minimal information exchange
    - Refinements on interfaces, data types, timing
  - Required
    - Good partitioning
    - Building blocks approach
- Working setup



Results Movie



Results & Discussion



- Trade-off Concurrent Design ⇔ Integration
  - Minimal design interaction
  - Minimal information exchange
    - Refinements on interfaces, data types, timing
  - Designers attitude
    - Focus on own partition, but think across discipline boundaries
- Possible Improvements
  - Model-based integration tests
    - Physical system model could be used to test the final software ⇔ Virtual Prototyping
  - Tool support:
    - Automated consistency checks
    - Tool ⇔ Tool integration
    - Model ⇔ Model interaction

Conclusions

- Mechatronics / Cyber Physical Systems
  - Synergistic design approach
  - Close cooperation between disciplines ⇔ integrated design
- Integrated design ⇔ concurrent design efficiency
  - Trade-off between early integration and late integration time
  - Choice is project specific
- Good partitioning of the mechatronic system
  - Allows concurrent, but partly separated design
- Case: fully integrated design is not always needed
  - More efficient work flow with still predictable integration
- Methodology not limited to SW implementation ECS
  - ECS in FPGA realization available

Ongoing work

- Embedded Control System software for our Humanoid Soccer Robot
  - Vision processing
  - Supervisory control
  - Sequence control
  - Path planning
  - Soccer strategy
  - Low level loop control
    - 24 degrees of freedom