Embedding Formal Techniques into Industrial Product Development

Experiences with the DESTECS approach

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*Joint work with John Fitzgerald, Peter Gorm Larsen, Bert Bos,
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and (many) others*

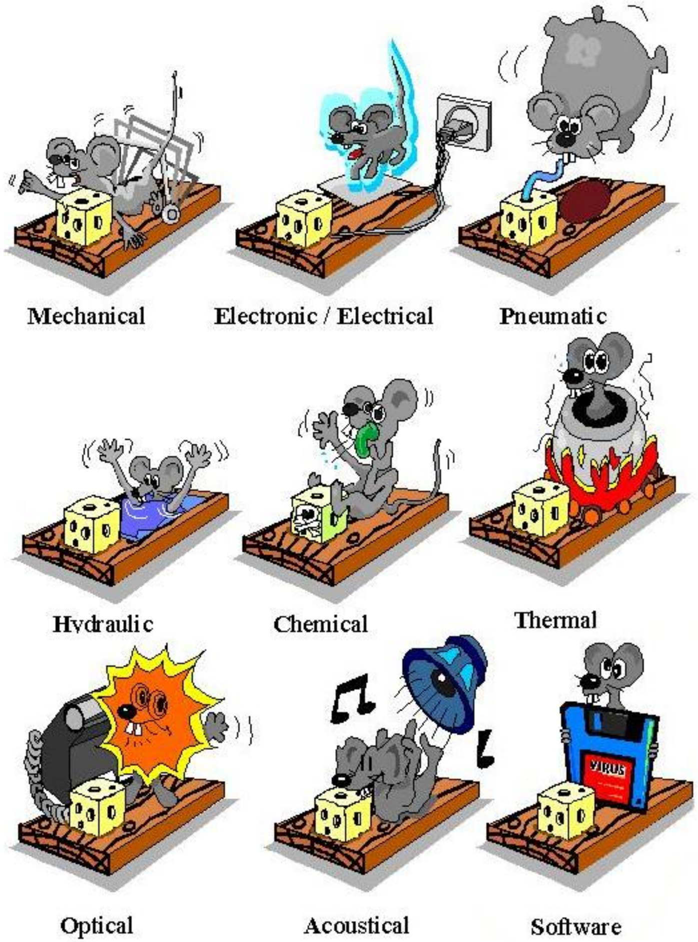
Overview of this talk

- **Challenges in developing dependable embedded systems**
- **Collaborative modeling: the DESTECS approach**
- **Example industrial applications**
- **Live tool demo**
- **Conclusions**

Embedded Systems Development (1)

- **Highly competitive marketplace:**
  - Requirements are volatile
  - Time to market is key
- **Products are complex**
- **Early design stages are vulnerable to failure:**
  - Engineering disciplines have distinct methods & tools
  - Design choices are often implicit or experience based
  - System dynamics are complex to grasp and express
  - Dependability (faults, fault tolerance) is often crucial

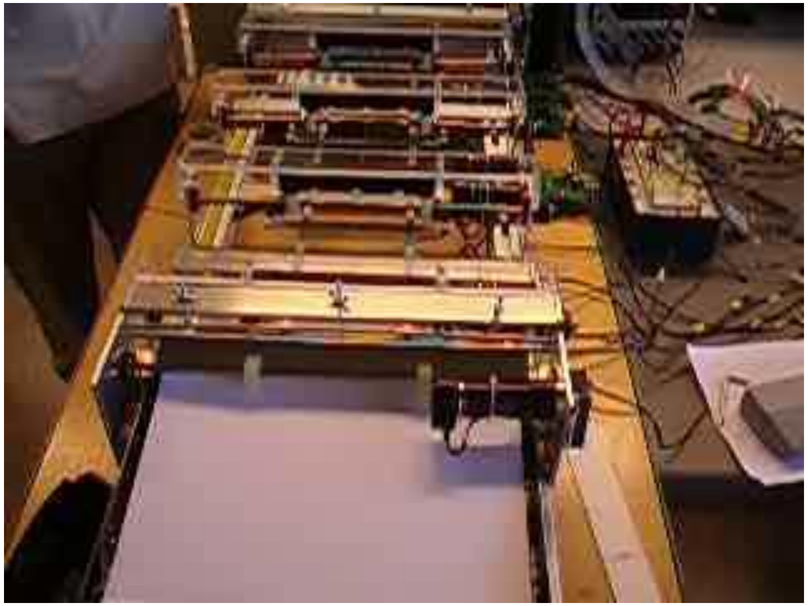
Embedded Systems Development (2)



- Problem decomposition into disciplines
- Traditional approaches are "one discipline at a time"
- Concurrent engineering required to improve time to market
- … but important properties are multidisciplinary
- … and so weaknesses are exposed late (integration)
- So: how to cross the boundaries between disciplines?

Embedded Systems Development (3)

- Design gaps between disciplines lead to errors in designs
- Many of these errors are detected too late: during testing of first physical prototype
- Example: paper path setup
- Paper jams for high speed paper handling



Embedded Systems Development (4)

Industial “holy grail” : Design Space Exploration

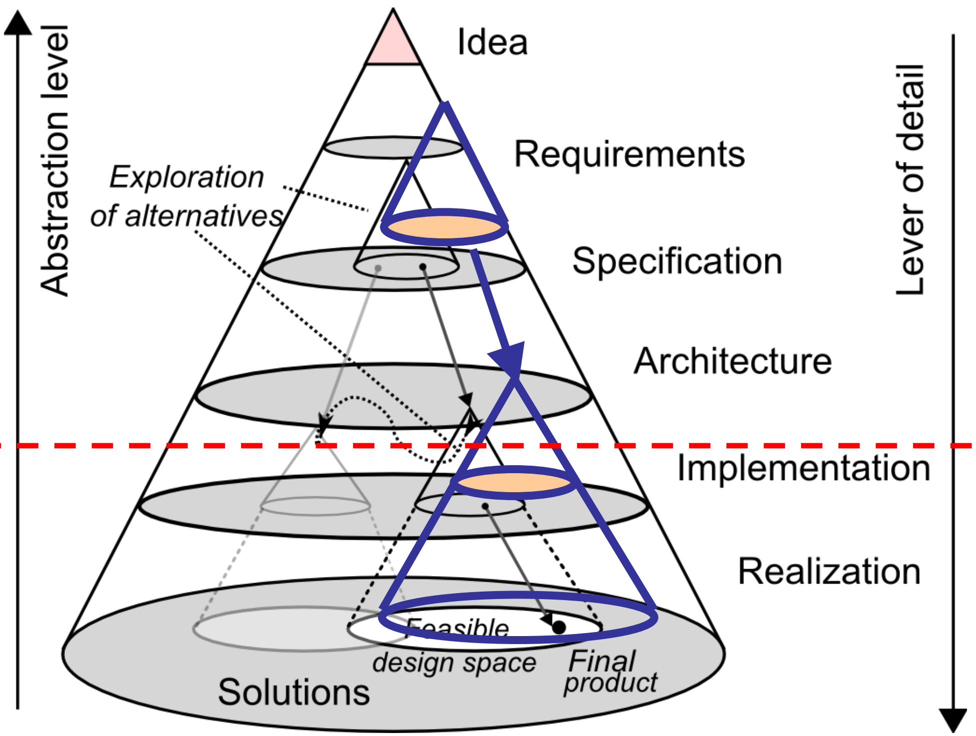
Explore and restrict to feasible solutions

Managing space of models (patterns)

Visualisation of test outcomes

“Ranking”

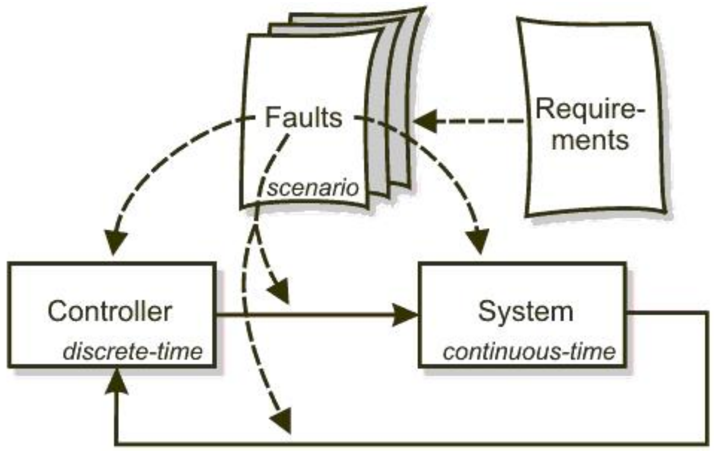
Managing scenarios



DESTECS (www.destecs.org)

- Bridge design gap between disciplines through co-simulation
- Develop methods and tools
- Modeling of faults and fault tolerance mechanisms

VDM (Overture)



Bond graphs (20-sim)

- Restriction to discrete-event domain and continuous-time domain
- Industrial Follow Group will monitor results and provide challenges
- EU FP7 project runs from 01-2010 until 12-2012

DESTECS in a nutshell (1)

Model Based Design:

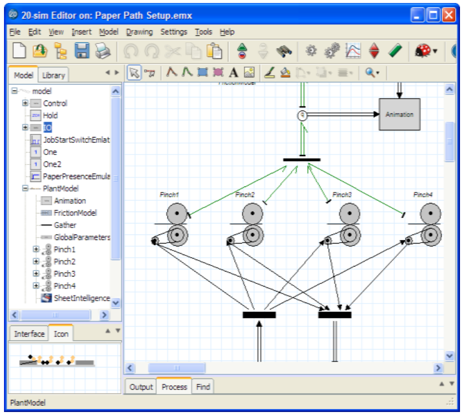
- controller in discrete event domain
- plant in continuous time domain

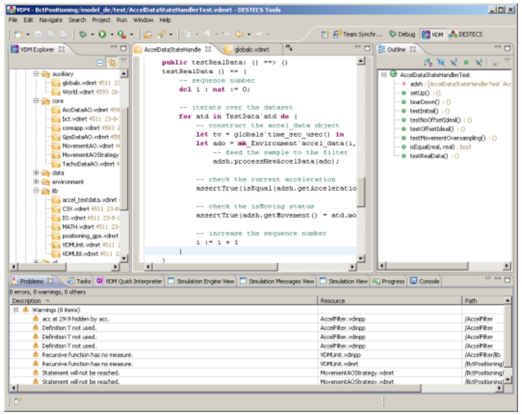
Co-simulation:

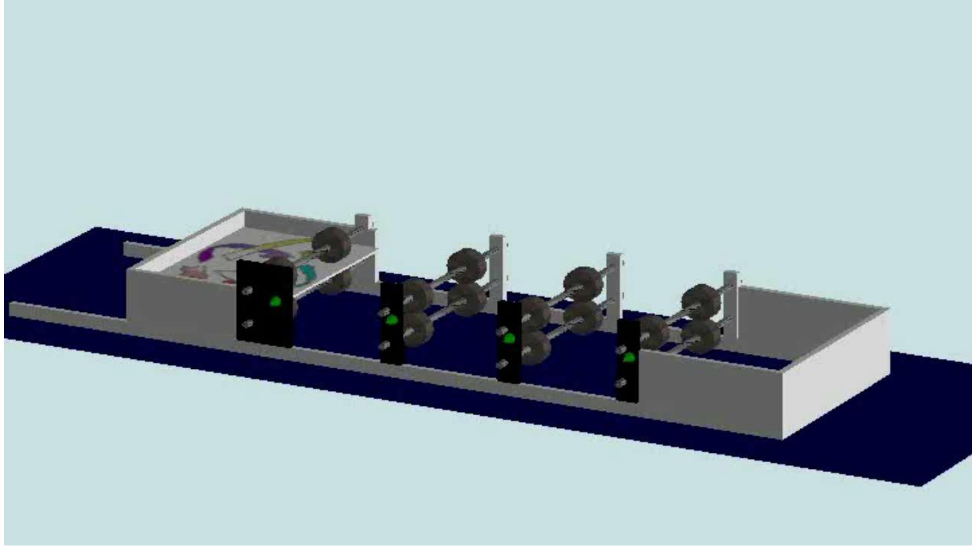
- coupling disciplines
- analysis on virtual prototype

Automated Co-model Analysis

Methodological guidelines



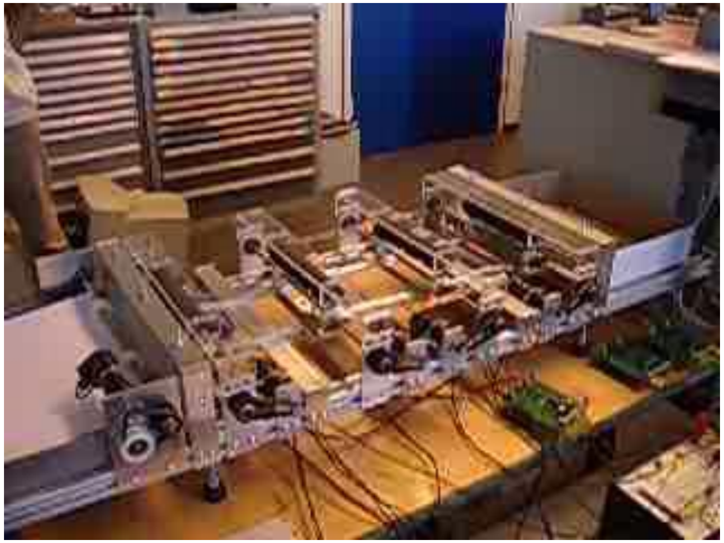




DESTECS in a nutshell (2)

Cause of the problems

- Geometry changes were not adequately communicated
- Errors in acceleration and deceleration paths



Results

- These errors can be detected in an early stage of the design through co-simulation
- Dependability can be assessed by fault injection

Marcel Verhoef, Peter Visser, Jozef Hooman, Jan Broenink. *Co-simulation of Real-time Embedded Control Systems*, LNCS 4591, Integrated Formal Methods IFM 2007, pp. 639-658, 2007

Zoe Andrews, John Fitzgerald, Marcel Verhoef. *Resilience Modelling Through Discrete Event and Continuous Time Co-Simulation*, Dependable Systems and Networks (July 2007).

Modelling & Simulation

Model

Abstract
Competent if detailed enough for analysis
Variables
Design Parameters fixed per run

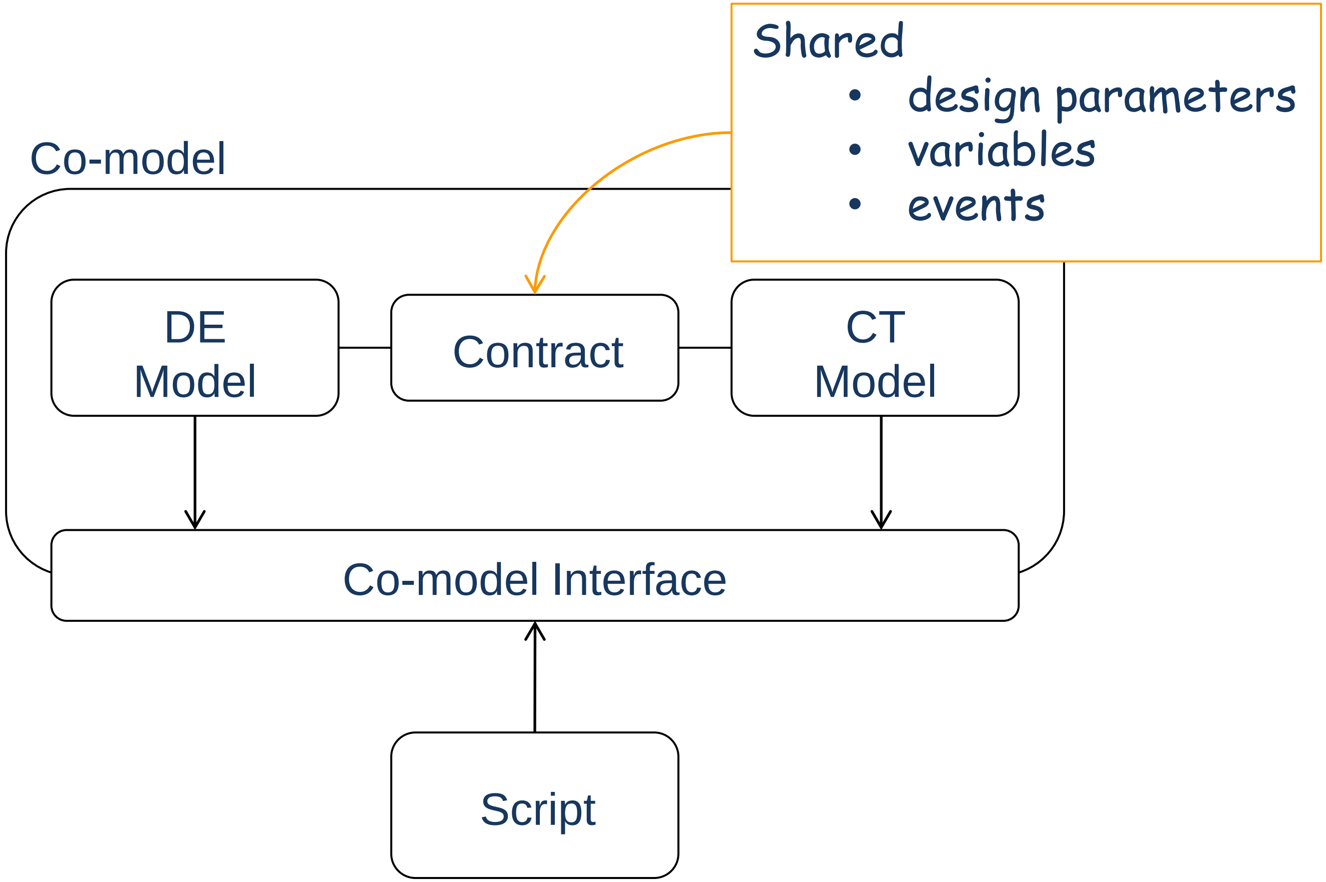
Model Interface

Script

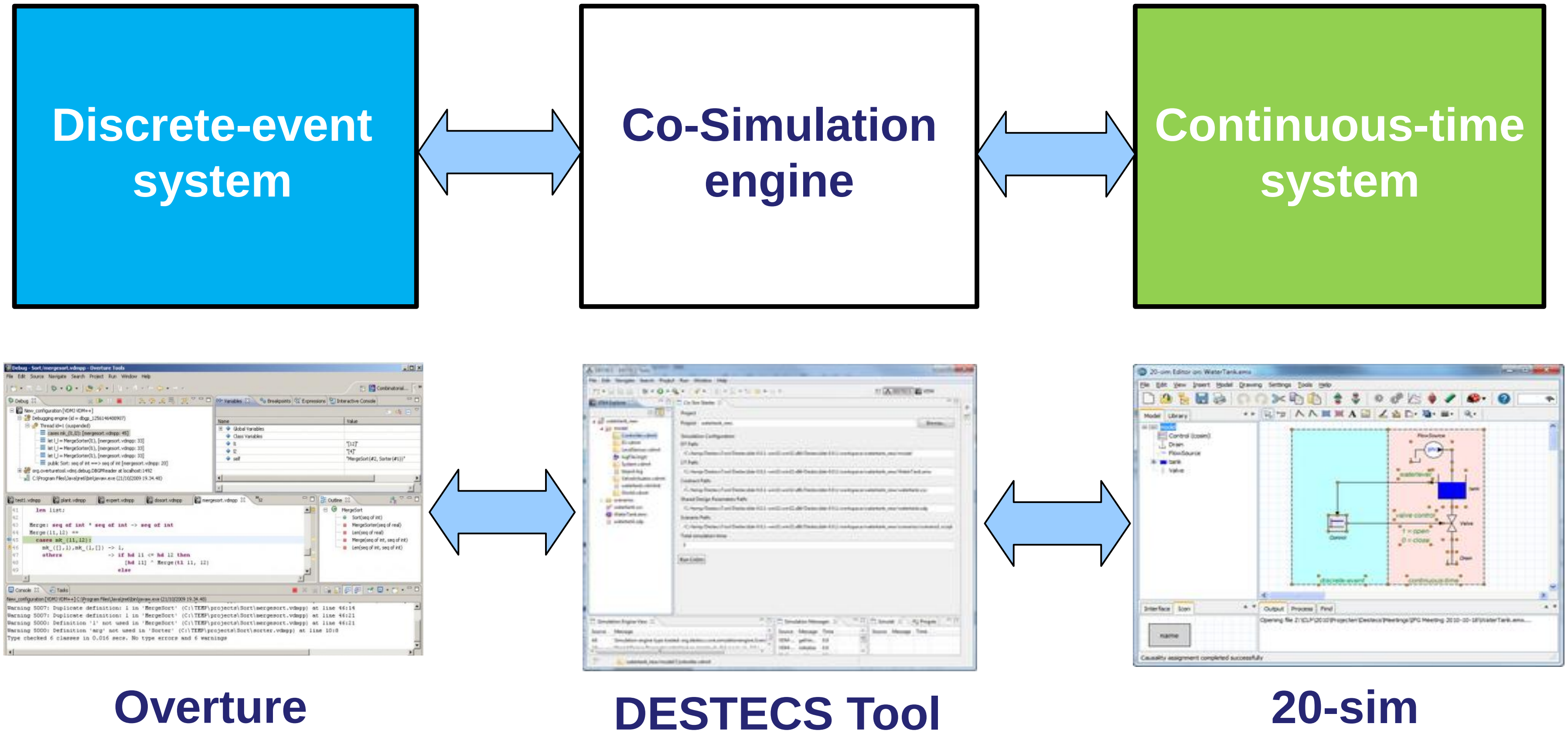
Faults – errors – failures
Fault Modelling: including error states & faulty functionality in the model
Fault Injection during a simulation managed by script

Runs a **simulation**
Initialises variables and design parameters
Forces selections and external updates, e.g. set point

co-modelling & co-simulation

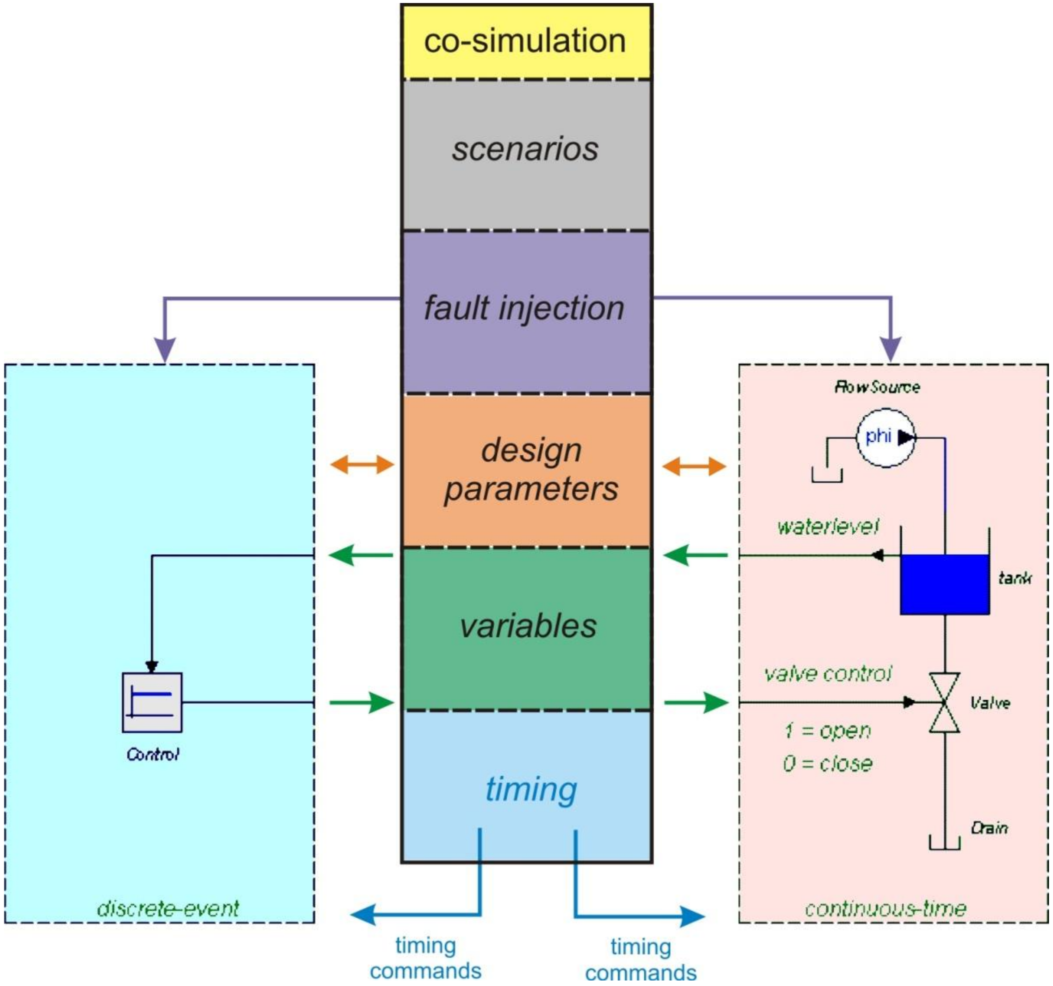


DESTECS Tool Architecture

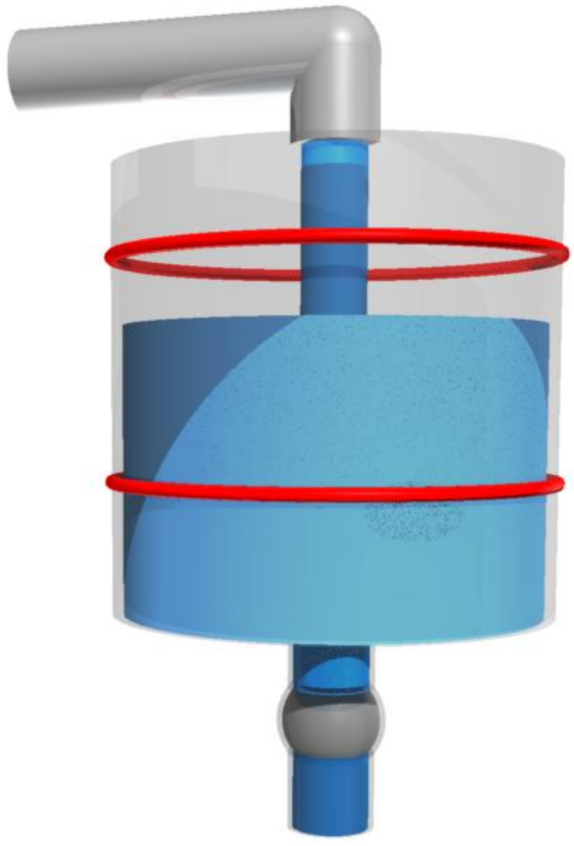


Formally specified semantics of the DE / CT integration (SOS)

Co-Simulation architecture



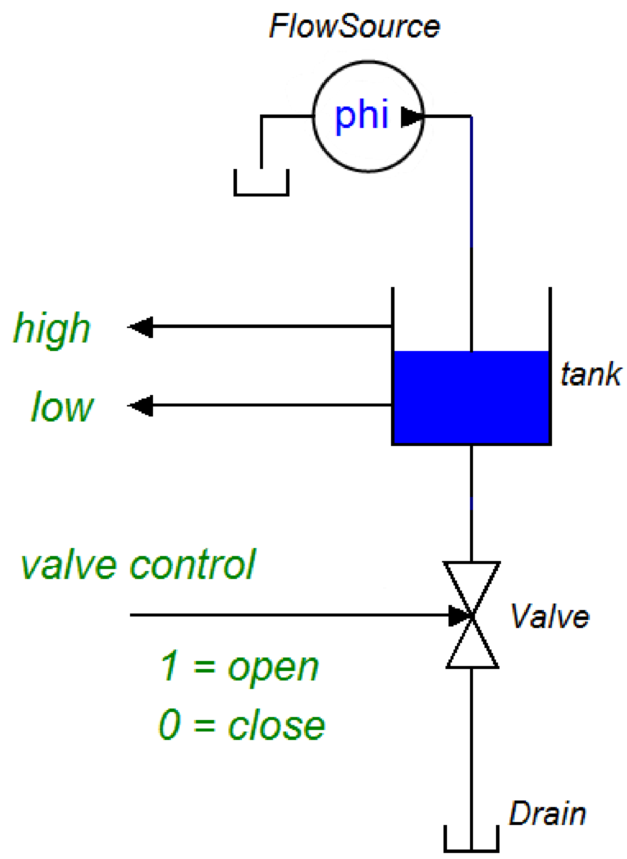
Example: water tank



$$\frac{dV}{dt} = \varphi_{in} - \varphi_{out}$$

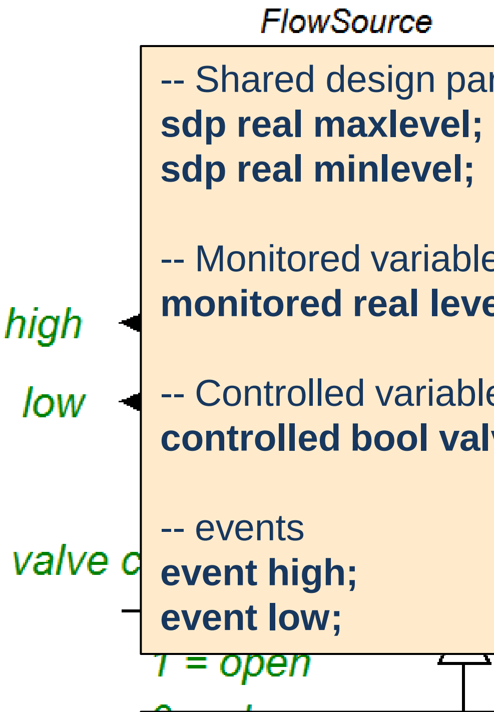
$$\varphi_{out} = \begin{cases} \frac{\rho \cdot g}{A \cdot R} \cdot V \ if\ valve\ open \\ 0 \quad if\ valve\ closed \end{cases}$$

Example: water tank




```
class Controller

instance variables
 private i : Interface

operations
 async public Open:() ==> ()
 Open() == duration(50)
   i.SetValve(true);

 async public Close:() ==> ()
 Close() == cycles(1000)
   i.SetValve(false);

sync
 mutex(Open, Close);
 mutex(Open); mutex(Close)

end Controller
```

Example: water tank




```
class Controller

ables
Interface

 Open:() ==> ()
ration(50)
(true);

 Close:() ==> ()
ycles(1000)
(false);

Close);
 mutex(Close)

end Controller
```

-- Shared design parameters
sdp real maxlevel;
sdp real minlevel;

-- Monitored variables (seen from the DE controller)
monitored real level := 0.0;

-- Controlled variables (seen from the DE controller)
controlled bool valve := false;

-- events
event high;
event low;

-- link events to operations
event high = System.Controller.Open;
event low = System.Controller.Close;

Example: water tank

This is VDM-RT: real-time extensions

Interface manages the shared variable for the valve setting.

duration constrain (absolute) time taken by the **async**hronous ops.

cycles constrain (relative) time taken by the ops, depending on deployment

Single active thread accessing the valve

```
class Controller

instance variables
 private i : Interface

operations
 async public Open:() ==> ()
 Open() == duration(50)
   i.SetValve(true);

 async public Close:() ==> ()
 Close() == cycles(1000)
   i.SetValve(false);

sync
 mutex(Open, Close);
 mutex(Open); mutex(Close)

end Controller
```

Example: modelling faults

```
class ValveActuator
types
ValveCommand = <OPEN> | <CLOSE>;
instance variables
 private i : Interface;


operations
```

```
public Command: ValveCommand ==> ()
 Command(c) == duration(50)

   cases c:
    <OPEN> -> i.SetValve(true),
    <CLOSE> -> i.SetValve(false)
   end

 post i.ReadValve() <=> c = <OPEN> and
      not i.ReadValve() <=> c = <CLOSE>



end ValveActuator
```

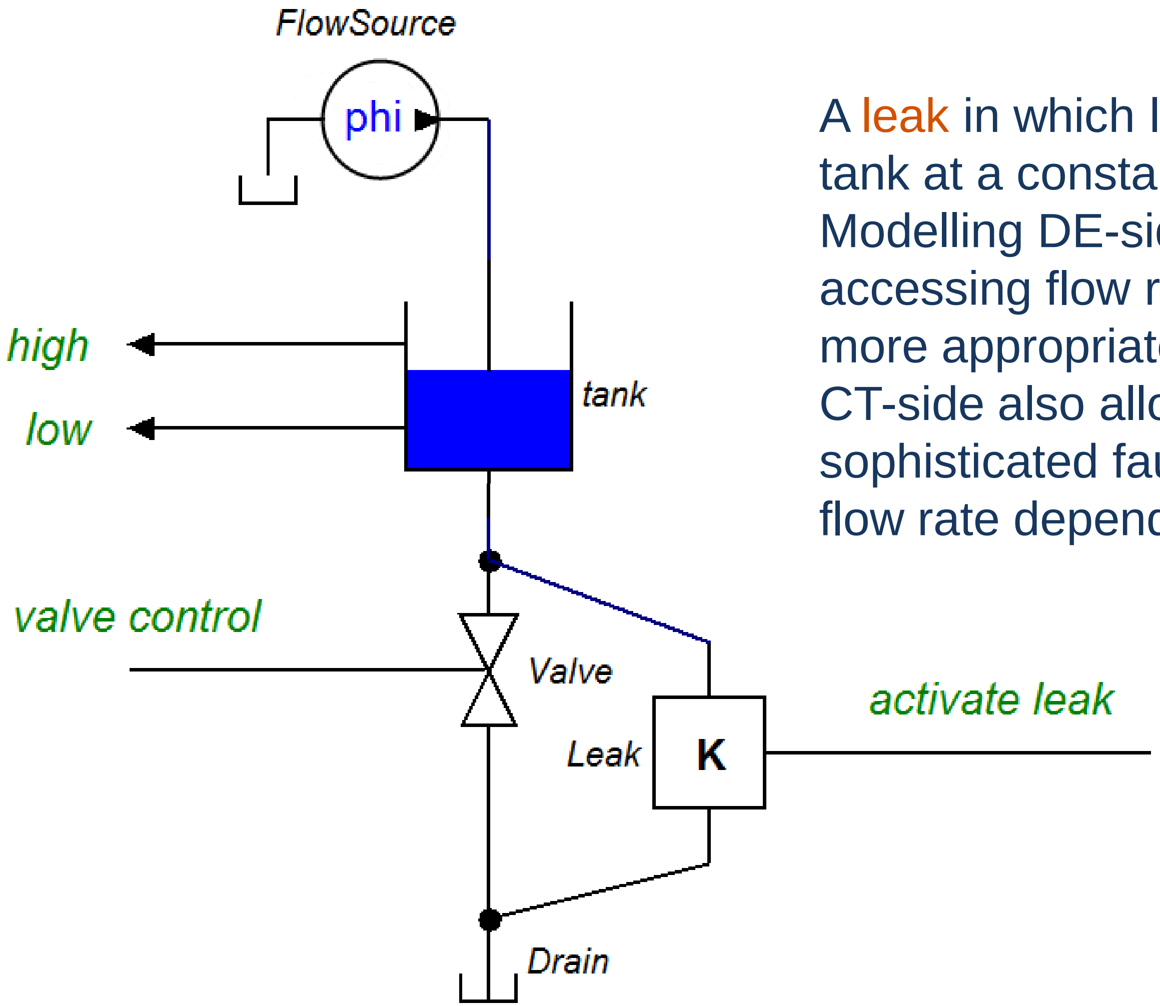
Example: modelling faults

A stuck valve …

```
class ValveActuator
types
ValveCommand = <OPEN> | <CLOSE>;
instance variables
 private i : Interface;
 private stuck : bool := false

operations

 private SetStuckState: bool ==> ()
 SetStuckState(b) == stuck := b
 post stuck <=> b and not stuck <=> not b;
```

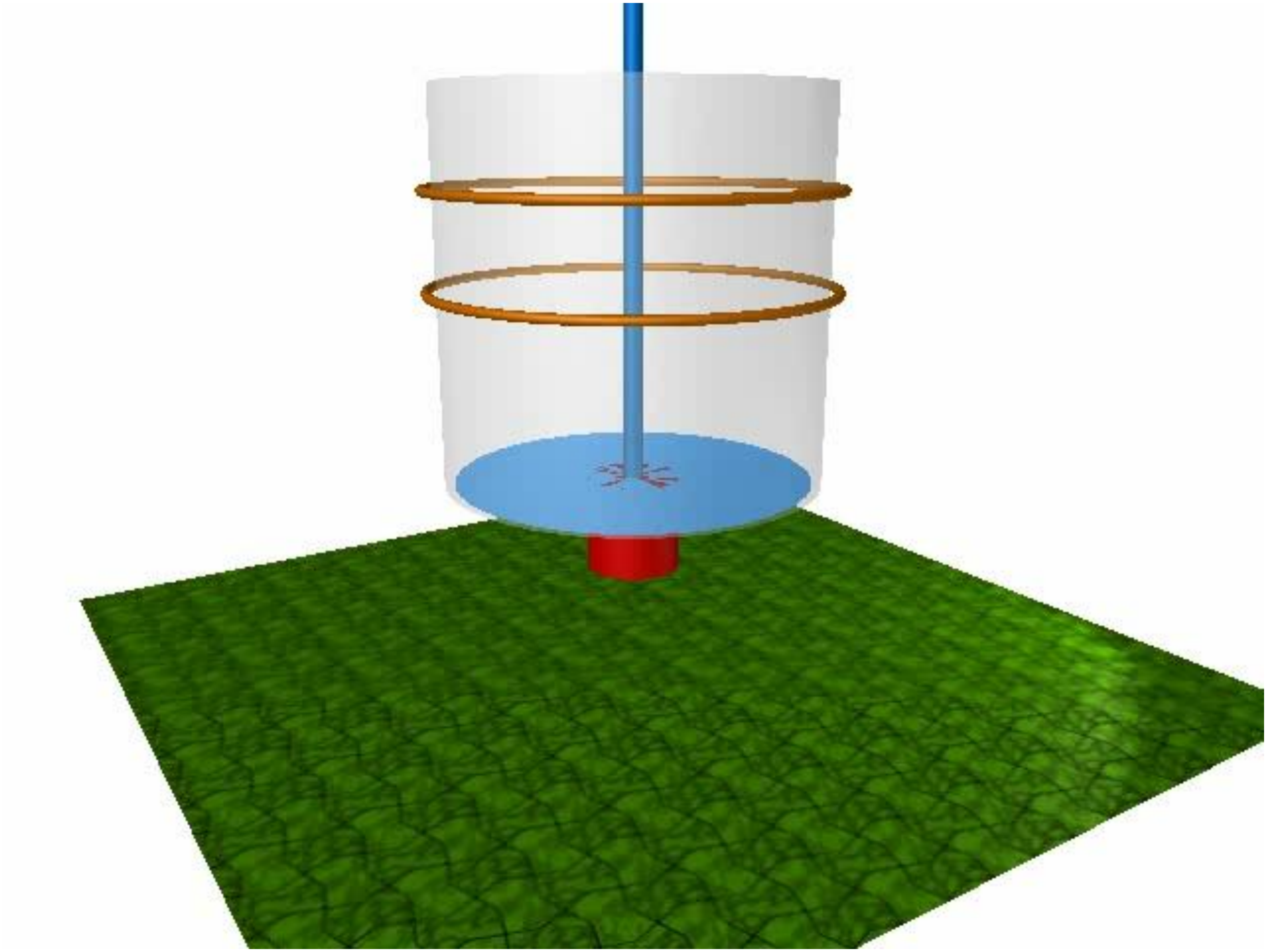
```
public Command: ValveCommand ==> ()
 Command(c) == duration(50)
   if not stuck then
   cases c:
    <OPEN> -> i.SetValve(true),
    <CLOSE> -> i.SetValve(false)
   end
 pre not stuck
 post i.ReadValve() <=> c = <OPEN> and
      not i.ReadValve() <=> c = <CLOSE>
 errs STUCK : stuck ->
             i.ReadValve() = ~i.ReadValve();

end ValveActuator
```

Example: modelling faults

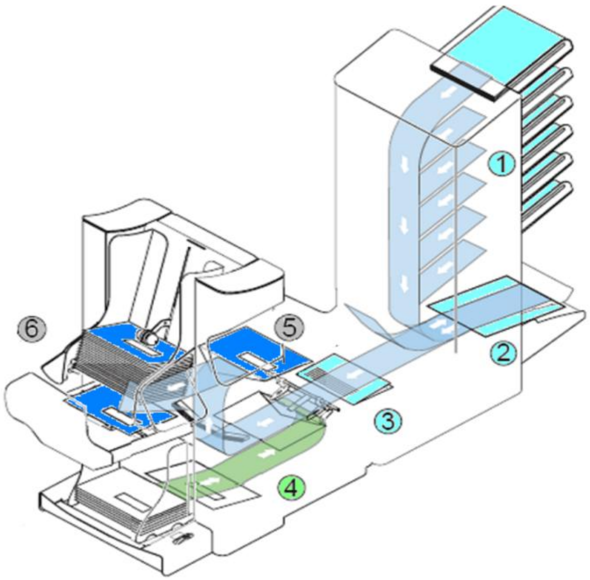


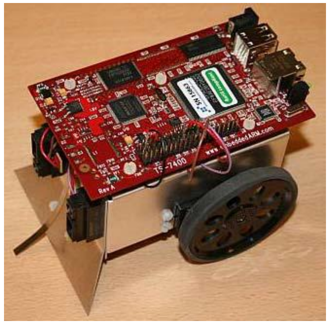
A leak in which liquid flows from the tank at a constant rate.
Modelling DE-side entails DE accessing flow rate. So this may be more appropriately modelled CT-side.
CT-side also allows for more sophisticated fault models, e.g. leak flow rate depends on pressure.

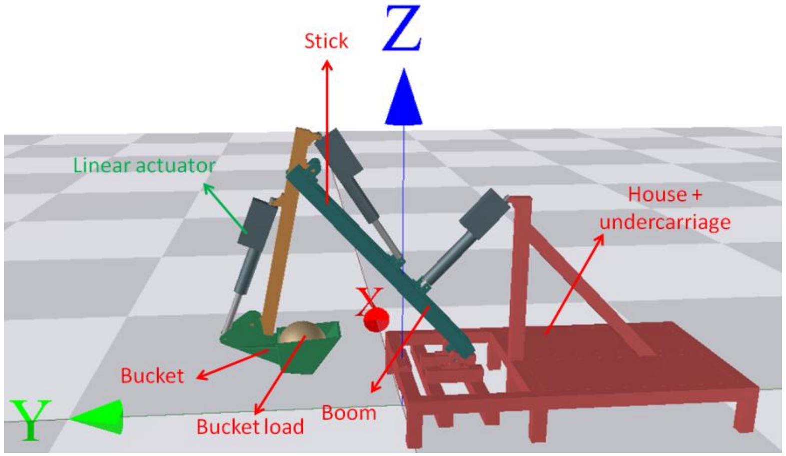
Example: water tank

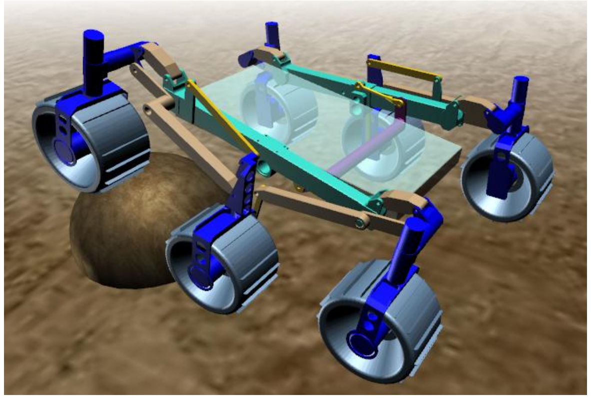


DESTECS case studies







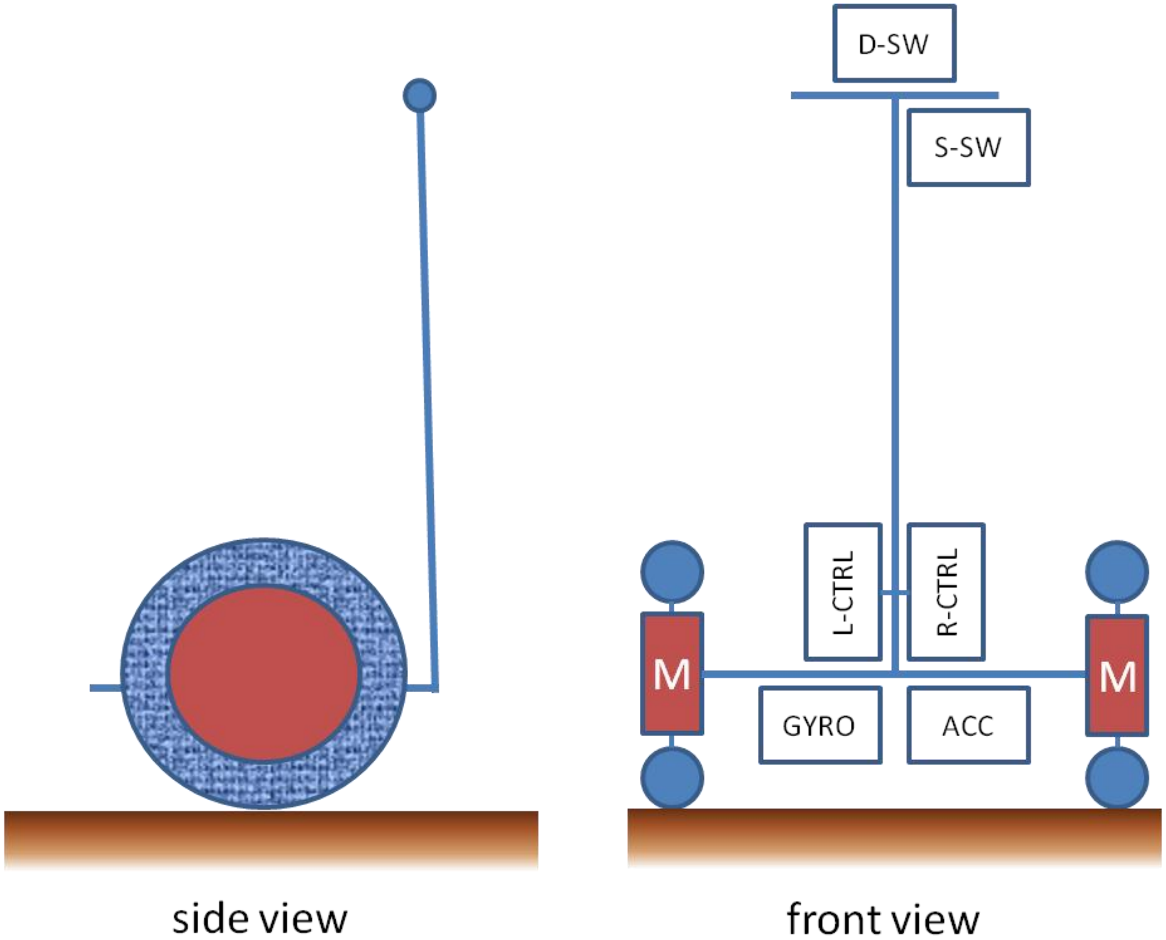


Chess – Self Balancing Scooter (1)

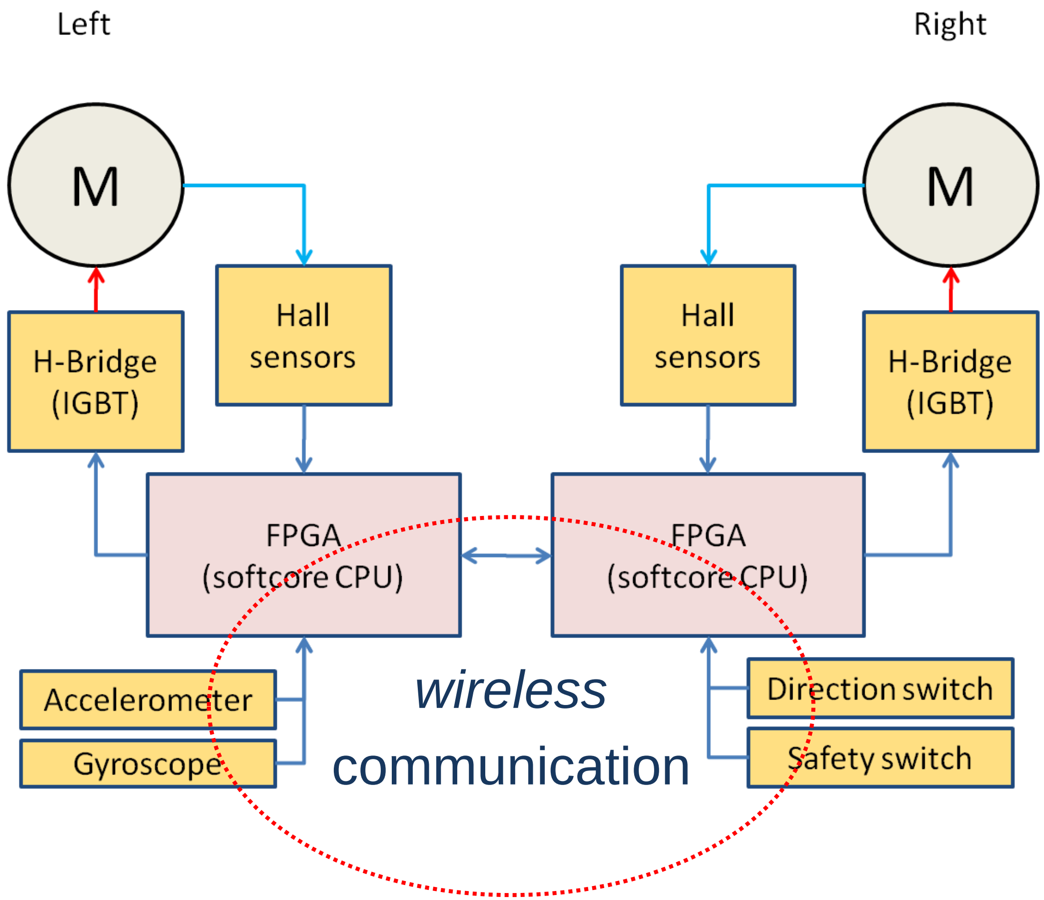
Chess – Self Balancing Scooter (2)

- **ChessWay is a technology and methodology demonstrator**
  - First generation: single controller driving both wheels
  - Second generation: two controllers, one driving a wheel each
  - Third generation: wireless communication sensors ↔ controllers
- **ChessWay exhibits typically modelling challenges common to many Chess products under development**
  - Simple nominal behavior, relatively easy to engineer
  - System behavior becomes very complex when faults and fault tolerance comes into play
  - Managing this complexity is the key to improve productivity (pre-empt cost for complex system integration and validation)
- **Typical design questions we want to address a-priori:**
  - Can we demonstrate the robustness of the ChessWay design?
  - Can we assess the impact of changes on the current design?

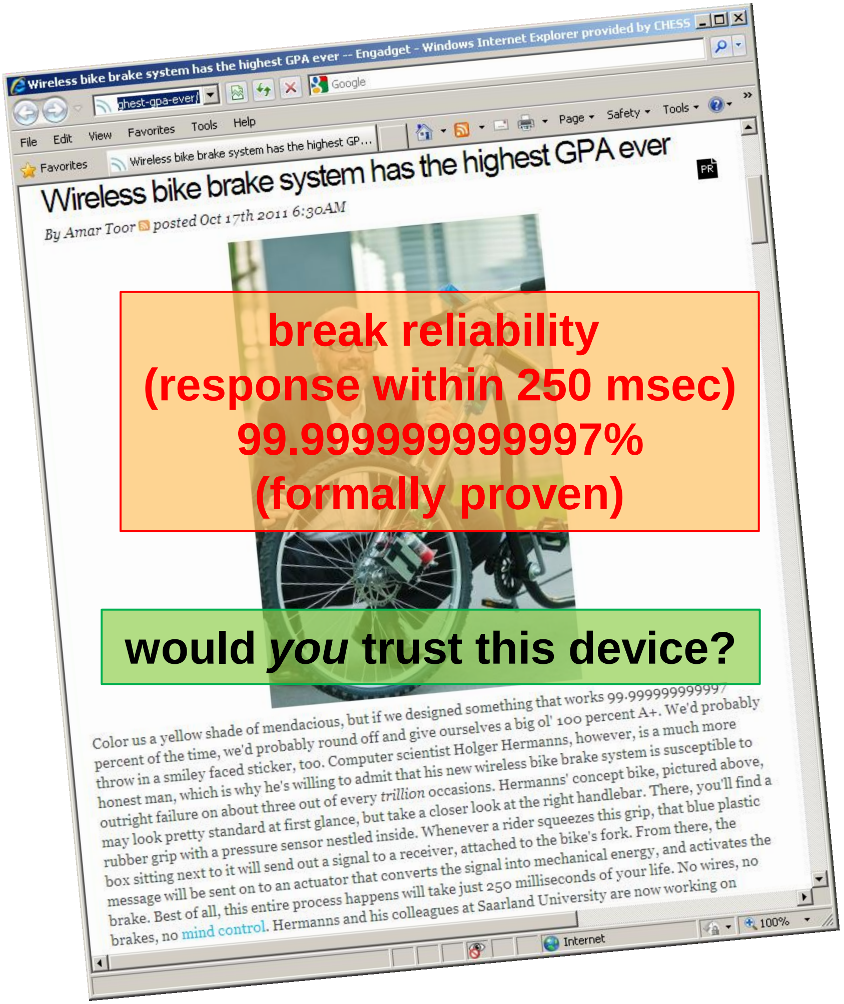
Chess – Self Balancing Scooter (3)



Chess – Self Balancing Scooter (4)



No Wires? *Have You Lost Your Mind?*

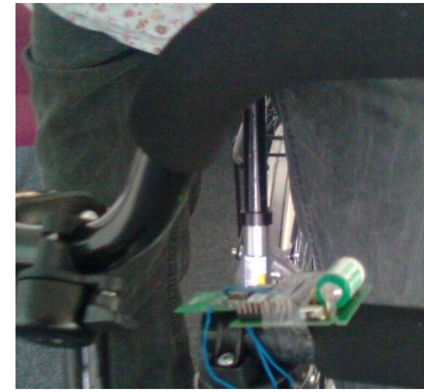

Wireless bike brake system has the highest GPA ever

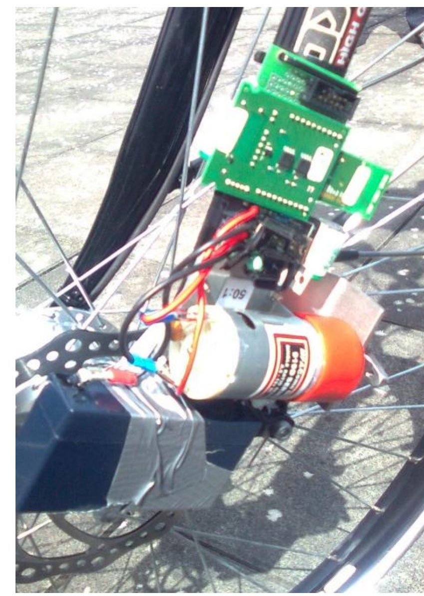
By Amar Toor posted Oct 17th 2011 6:30AM

Color us a yellow shade of mendacious, but if we designed something that works 99.999999999997 percent of the time, we'd probably round off and give ourselves a big ol' 100 percent A+. We'd probably throw in a smiley faced sticker, too. Computer scientist Holger Hermanns, however, is a much more honest man, which is why he's willing to admit that his new wireless bike brake system is susceptible to outright failure on about three out of every *trillion* occasions. Hermanns' concept bike, pictured above, may look pretty standard at first glance, but take a closer look at the right handlebar. There, you'll find a rubber grip with a pressure sensor nestled inside. Whenever a rider squeezes this grip, that blue plastic box sitting next to it will send out a signal to a receiver, attached to the bike's fork. From there, the message will be sent on to an actuator that converts the signal into mechanical energy, and activates the brake. Best of all, this entire process happens will take just 250 milliseconds of your life. No wires, no brakes, no mind control. Hermanns and his colleagues at Saarland University are now working on

break reliability
(response within 250 msec)
99.999999999997%
(formally proven)

would *you* trust this device?

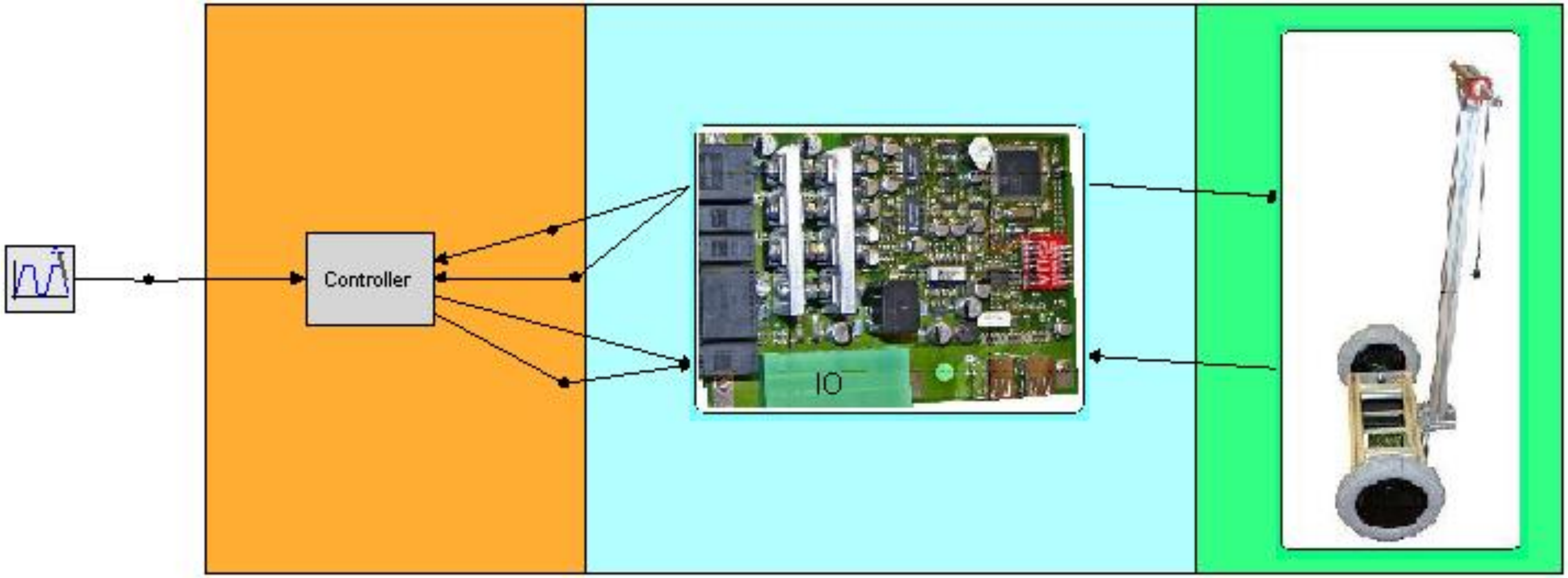




http://www.engadget.com/2011/10/17/wireless-bike-brake-system-has-the-highest-gpa-ever/

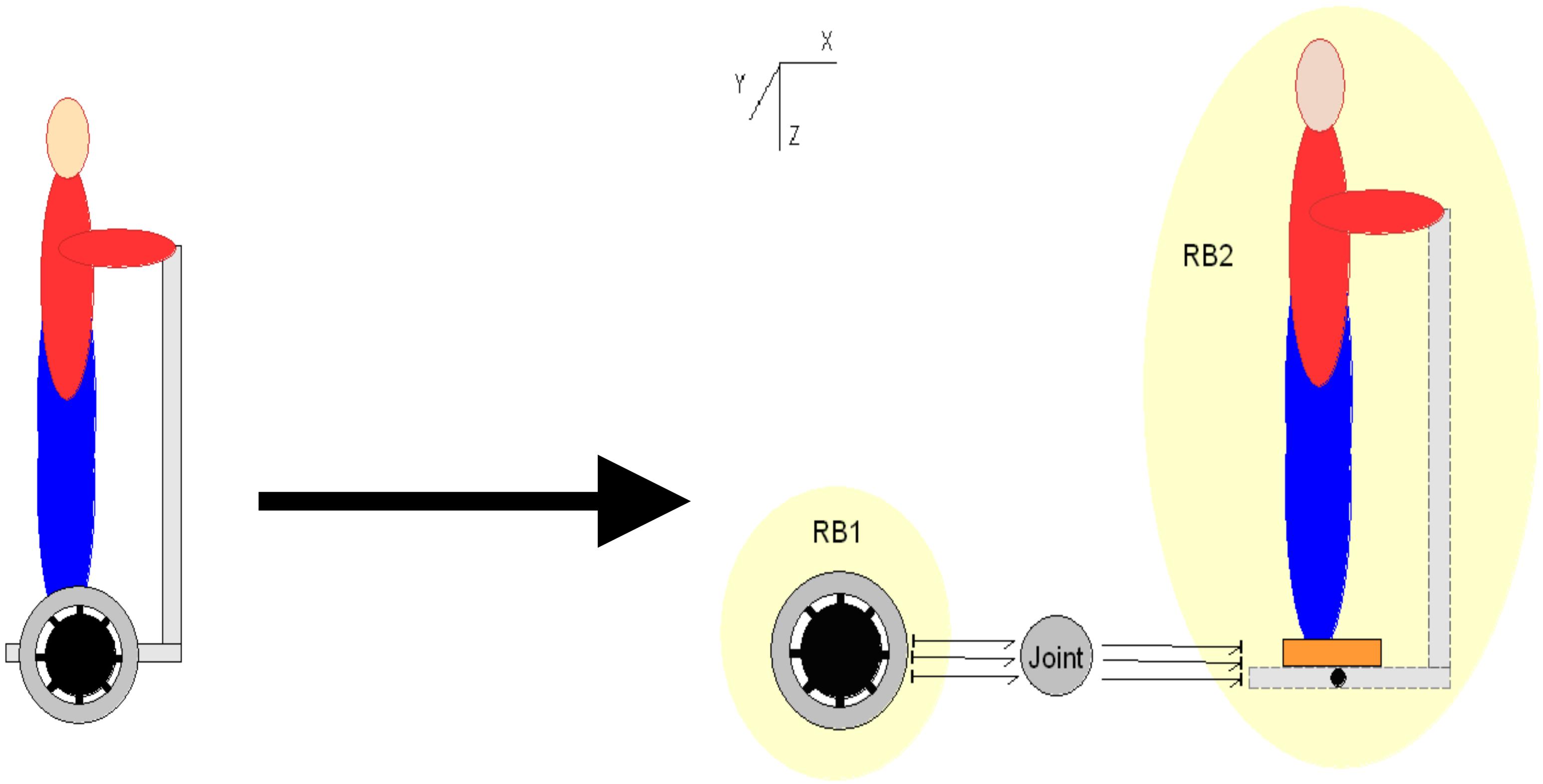
Modeling the SBS (1)

user behavior | controller | interface | plant

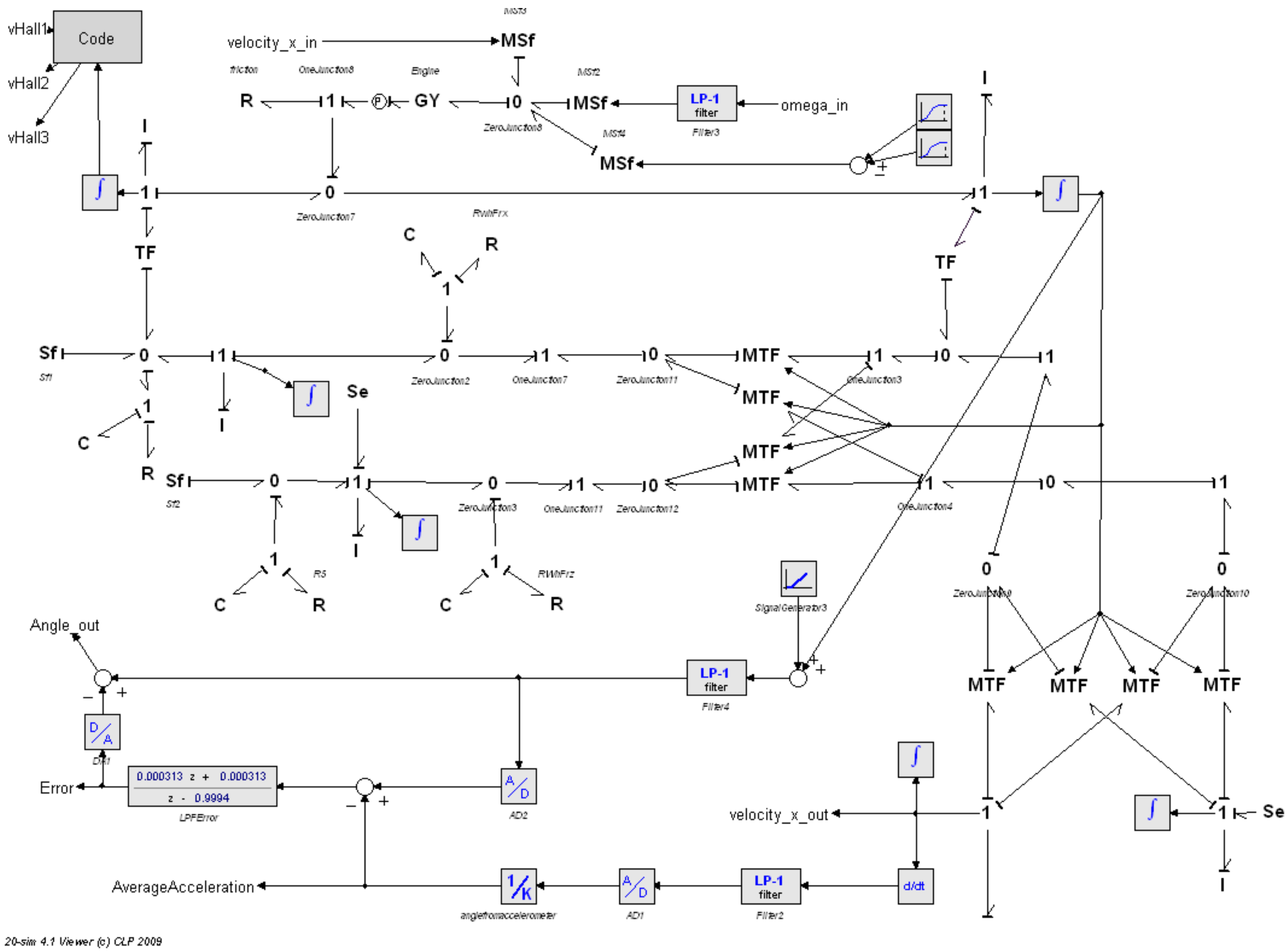


discrete event | contract | continuous time

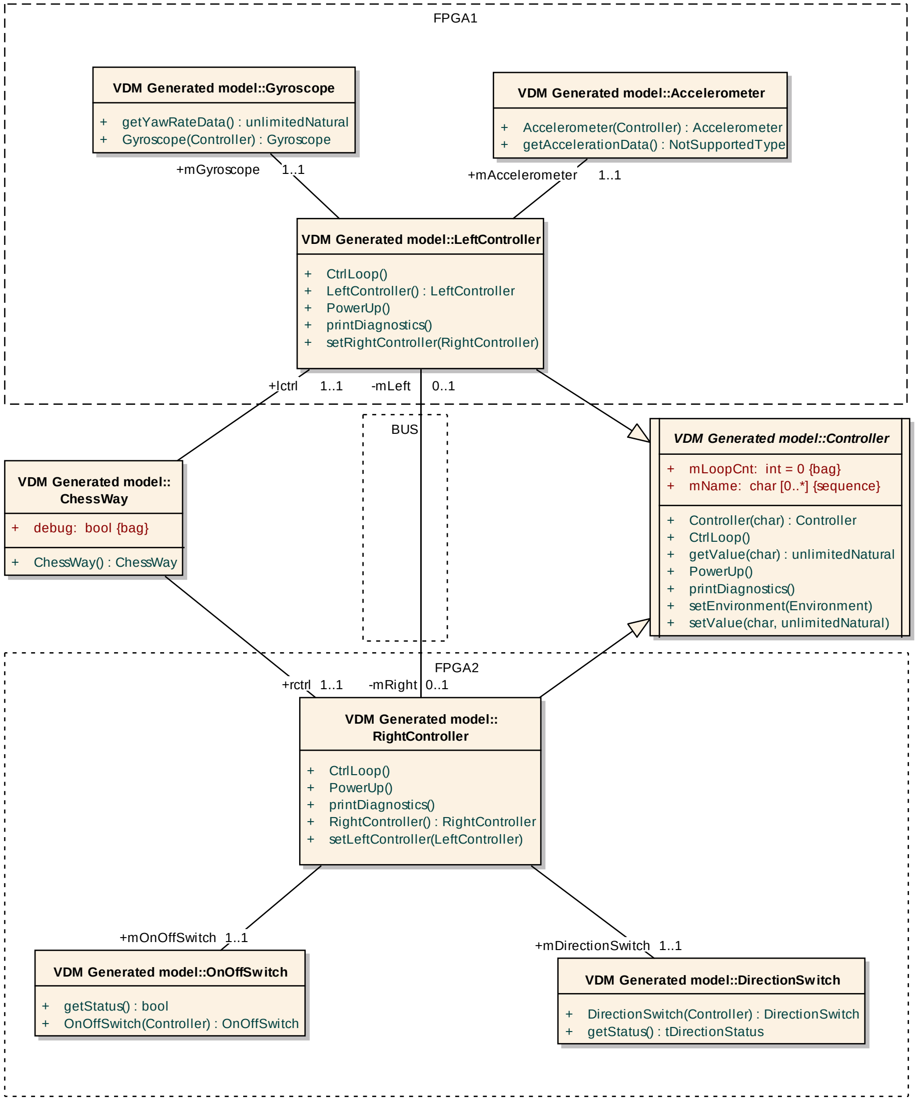
Modeling the SBS – continuous time (2)



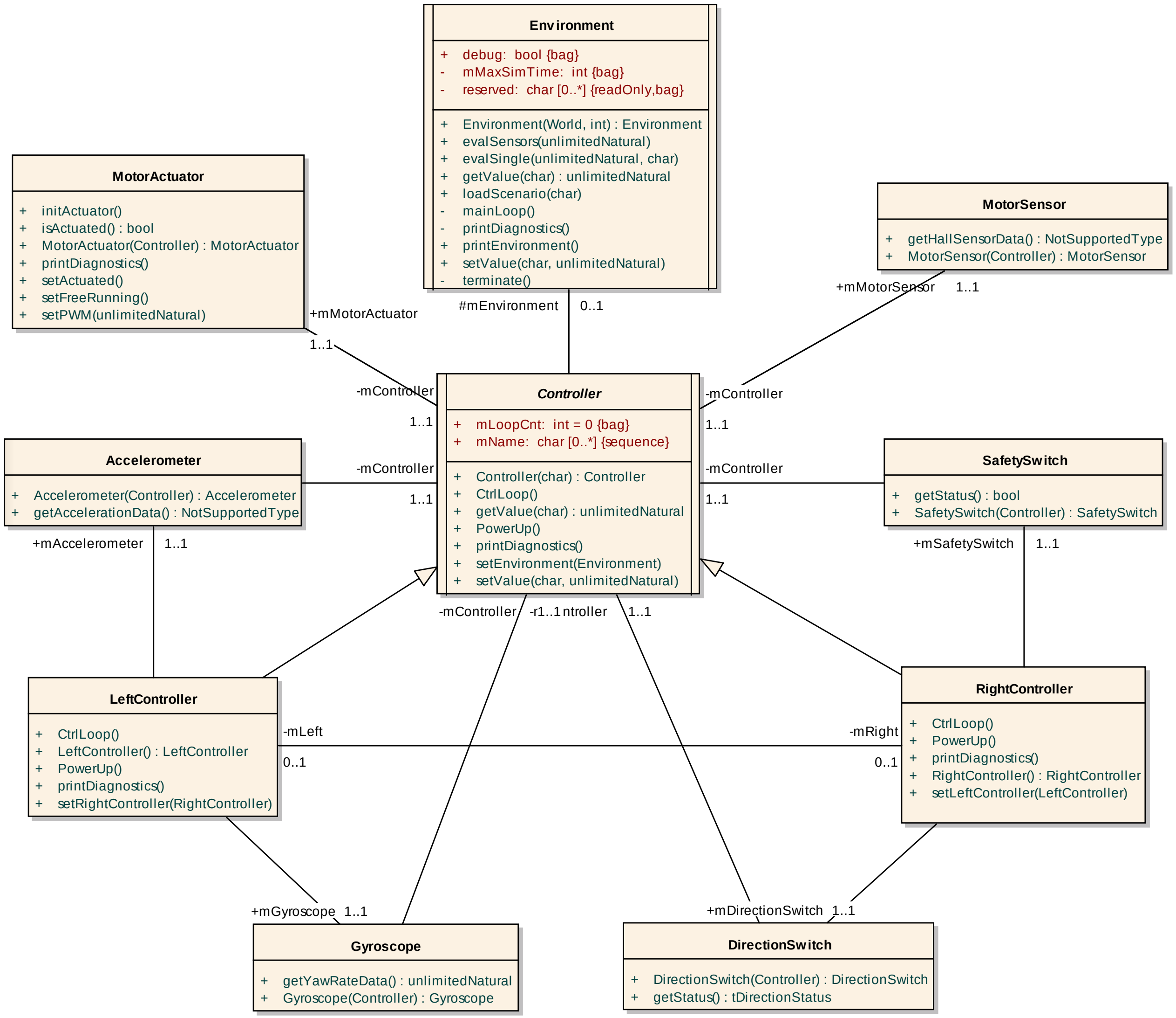
Modeling the SBS – continuous time (3)



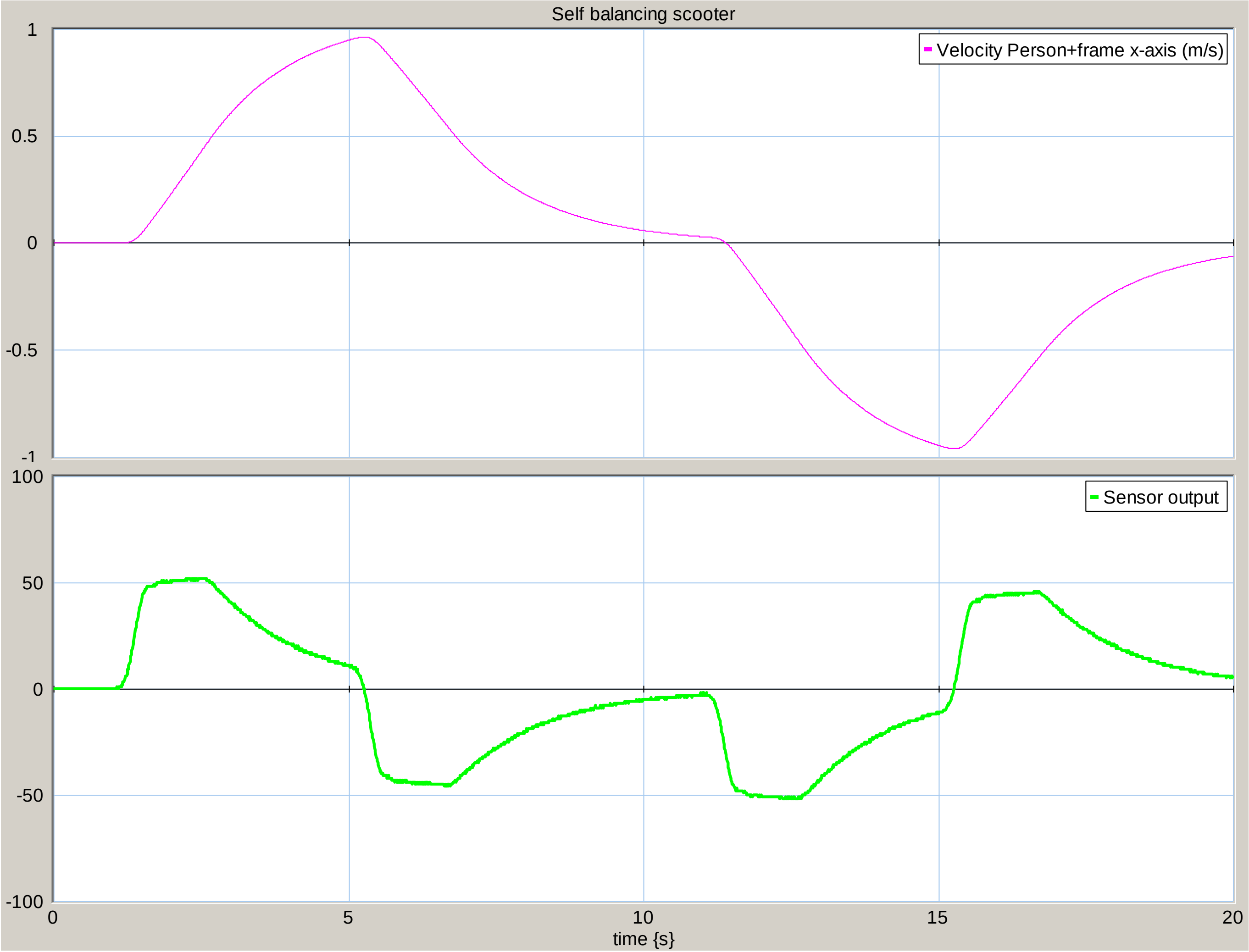
Modeling the SBS – discrete time (4)



Modeling the SBS – discrete time (5)



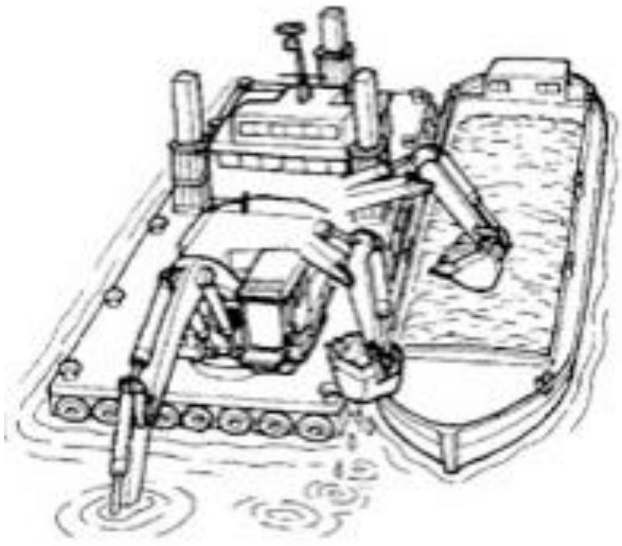
Analysis of SBS co-models (1)

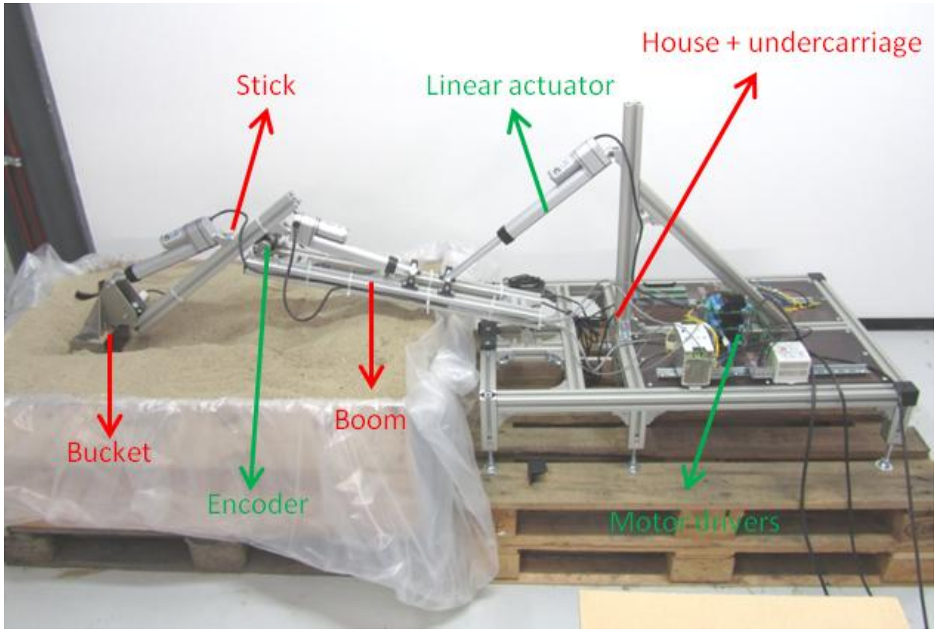


Analysis of SBS co-models (2)

CT model running in 20-sim and DE model running in Overture using DESTECS cosim tool
Movie available on http://www.destecs.org and http://www.youtube.com/watch?v=HccXkd4gWys

Verhaert – Dredging Excavator





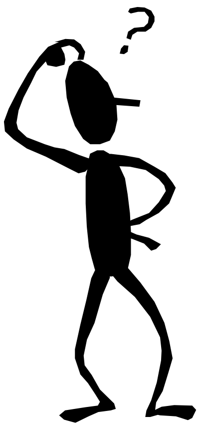
- **Overload and end-stop protection**
- **Emergency switch and system reset behavior**
- **Advanced operator assistance (i.e. perform a straight dig)**

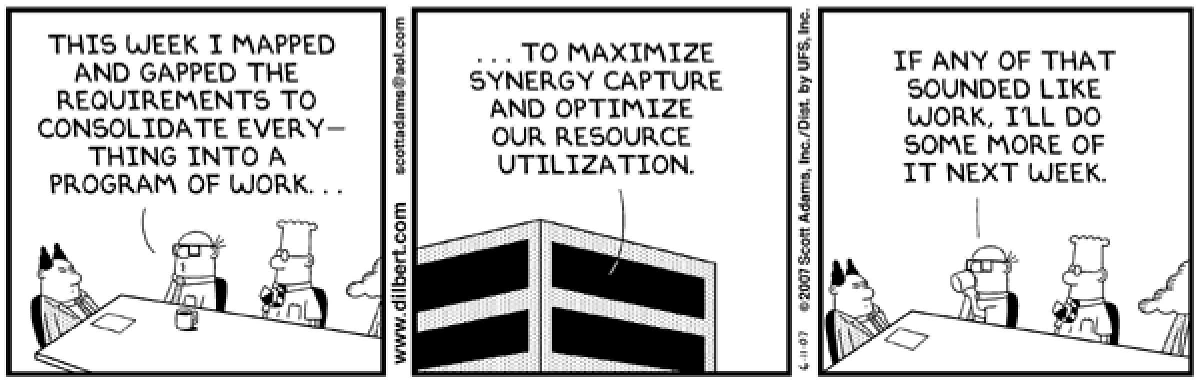
Observations and conclusions

- **Formal Methods helps to de-risk development**
  - including de-risking detailed formal analysis
  - providing rapid, accurate, but maybe incomplete analyses
  - training and methodological guidelines are crucial
  - start formal, (higher chance to) remain formal
- **What does formalism buy us?**
  - Sound semantic basis for the co-simulation tools & methods
  - Comprehensive analytic solutions are a long way off…
    … so (trustworthy) executable specifications are legit!
- **Co-modelling exposes issues that are often implicit**
  - In individual disciplines (we knew that already!)
  - And across boundaries, e.g. where to model faults
  - Expose potential problems earlier (no-brainer)
- **Co-simulation is enabler for Design Space Exploration**
- **Collaboration (also between researchers and practitioners ☺)**

thank you for your attention!

Any questions?





Some pointers to related information resources

`http://www.destecs.org`
`http://www.overturetool.org`
`http://www.20sim.com`
`http://www.vdmportal.org`