Part 1:
Co-modelling and Co-simulation

John Fitzgerald
Peter Gorm Larsen
Ken Pierce

Model-driven Design

- Modern systems are complex
- To cope with this, we can build models beforehand
  - To perform analysis (e.g. static analysis, proof, model checking, **simulation**)
  - Clarify our assumptions
  - Evaluate potential designs
  - Avoid expensive prototypes
- Different modelling paradigms for different aspects

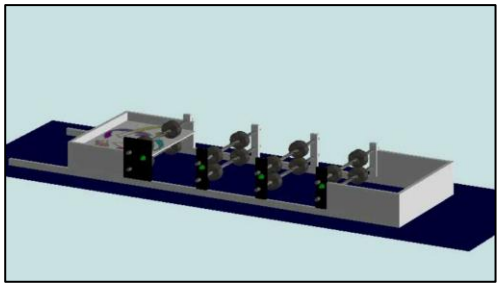
Modelling of Software

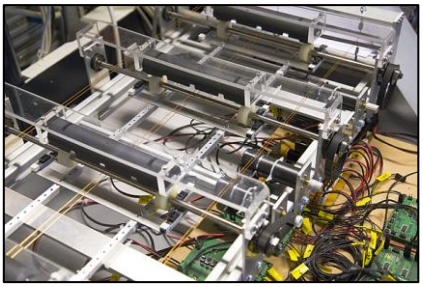
- Typically **discrete-event (DE),** e.g. VDM-RT
- In simulation, only the points in time at which the state changes are represented.
- Good abstractions for software
  - e.g. data types, object-orientation, threading
- Less suited for physical system modelling

- Typically **continuous-time (CT),** e.g. differential equations
- In simulation, the state changes continuously through time.
- Abstractions for disciplines, e.g. mechanical, electrical, hydraulic
- Poor software modelling support
  - only basic programming support; no functions or objects

Embedded Systems

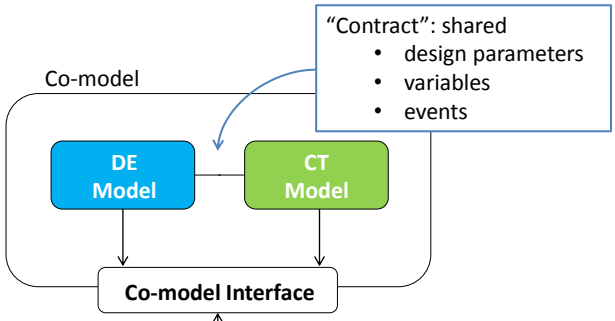
- Interacting computing, physical, human elements
- Increasingly complex logic (e.g. moding) ~80% of control software
- Error detection and recovery
- Collaborative development
- Diverse disciplines cultures, abstractions, formalisms
- Typically tackled separately
- Need for **design space exploration**





Co-modelling Concepts

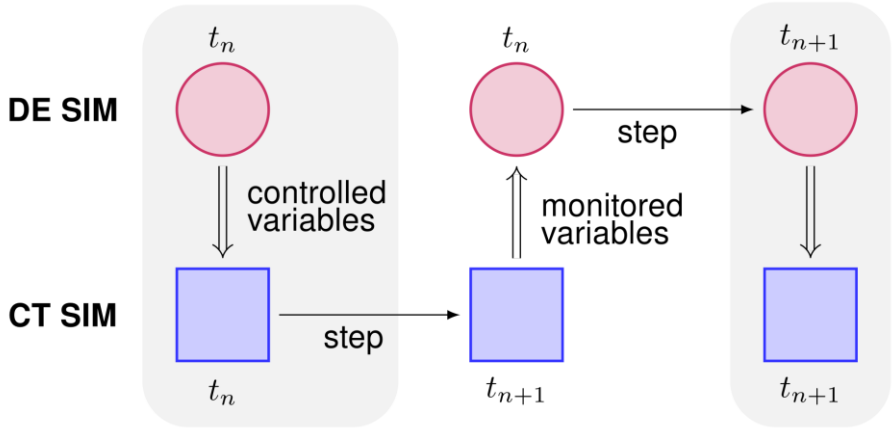
Variables modified during run
Design parameters fixed per run



Fault Modelling: including error states & faulty functionality in the model
Faults invoked during a simulation managed by script

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

Co-simulation Semantics



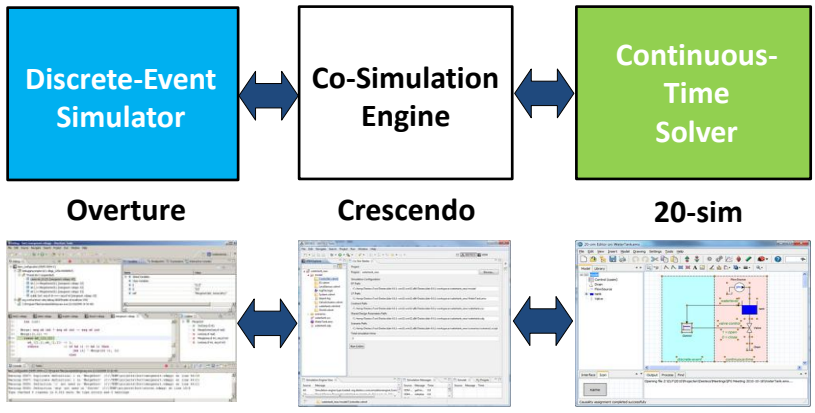
Co-simulation Semantics

- Simulators maintain local state / internal simulation time.
- Co-simulation engine synchronises:
  - shared variables, events, time
- Common time, t_n, at the start of a co-simulation step.
- DE simulator determines step length (to avoid roll-back).
- At t_n, the DE simulator:
  - sets controlled variables
  - proposes duration to for CT simulator to advance (if possible).
- Co-simulation engine tells the CT simulator to advance.

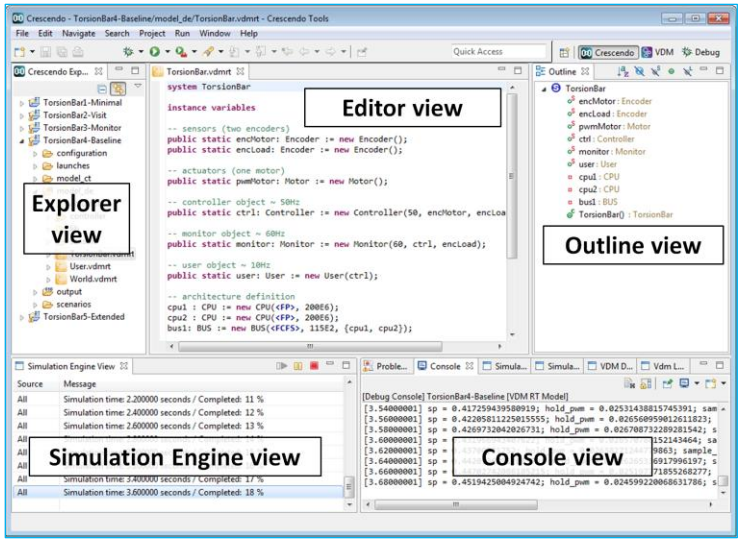
Co-simulation Semantics

- The CT simulator advances. If an event occurs before the proposed step time is reached, CT simulator stops early.
- Once the CT simulator has paused (reaching internal time t_{n+1}), the monitored variables and the actual time reached in the CT simulation are communicated back to the DE simulator.
- The DE simulation then advances so that both DE and CT are again synchronised at the same simulation time.
- *Cycle repeats.*

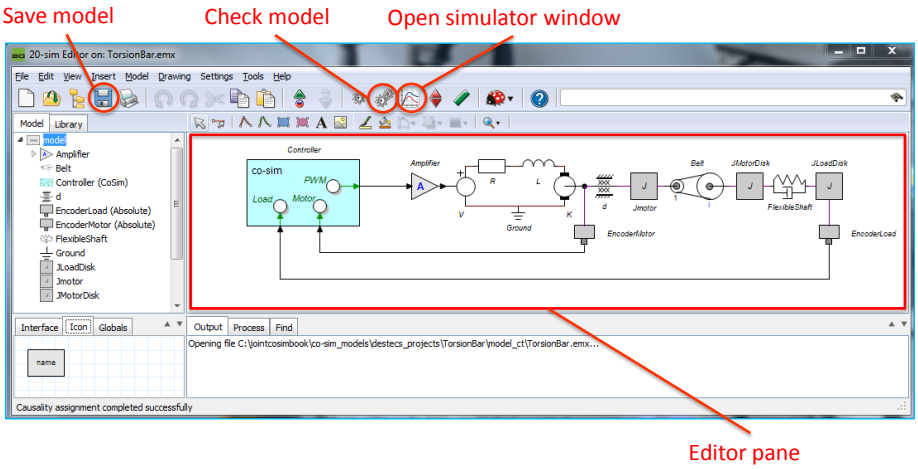
Background: Co-simulation



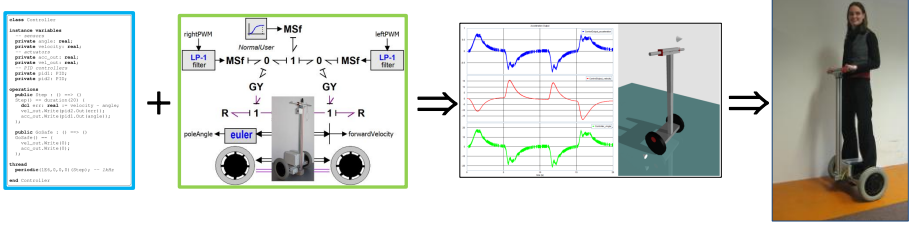
Crescendo Screenshot



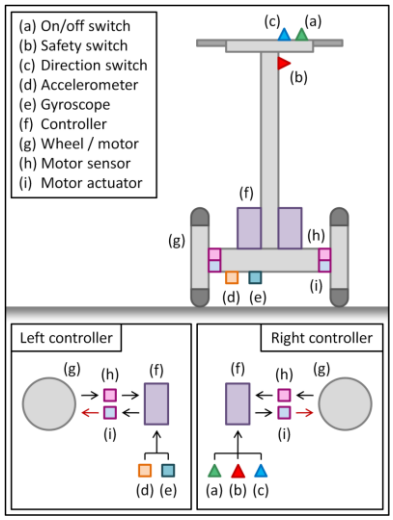
20-sim Screenshot



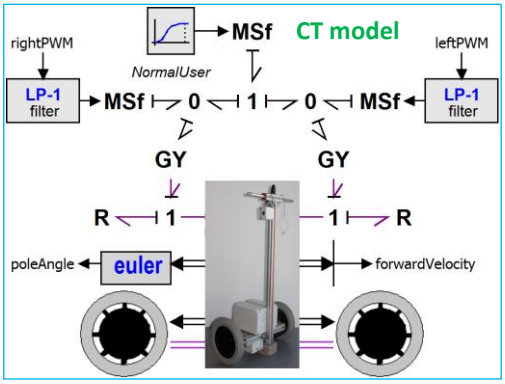
Example: Self-balancing Scooter



Example: Self-balancing Scooter



Example: Self-balancing Scooter



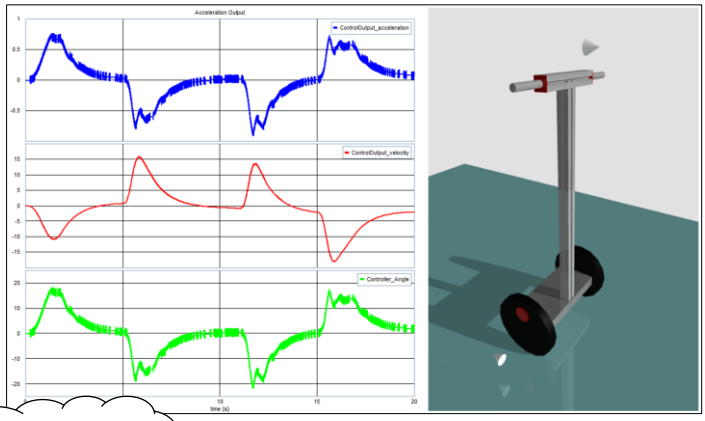
	Name	Type	Notes
controlled	leftPWM	real	range: [-1,1]
	rightPWM	real	range: [-1,1]
monitored	poleAngle	real	range: $[0,2\pi]$
	forwardVelocity	real	

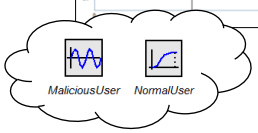
Contract

DE model

```
class Controller

instance variables
  -- sensors
  private angle: real;
  private velocity: real;
  -- actuators
  private acc_out: real;
  private vel_out: real;
  -- PID controllers
  private pid1: PID;
  private pid2: PID;

operations
  public Step : () ==> ()
  Step() == duration(20) (
    dcl err: real := velocity - angle;
    vel_out.Write(pid2.Out(err));
    acc_out.Write(pid1.Out(angle));
  );

  public GoSafe : () ==> ()
  GoSafe() == (
    vel_out.Write(0);
    acc_out.Write(0);
  );

thread
  periodic(1E6,0,0,0)(Step); -- 1kHz

end Controller
```

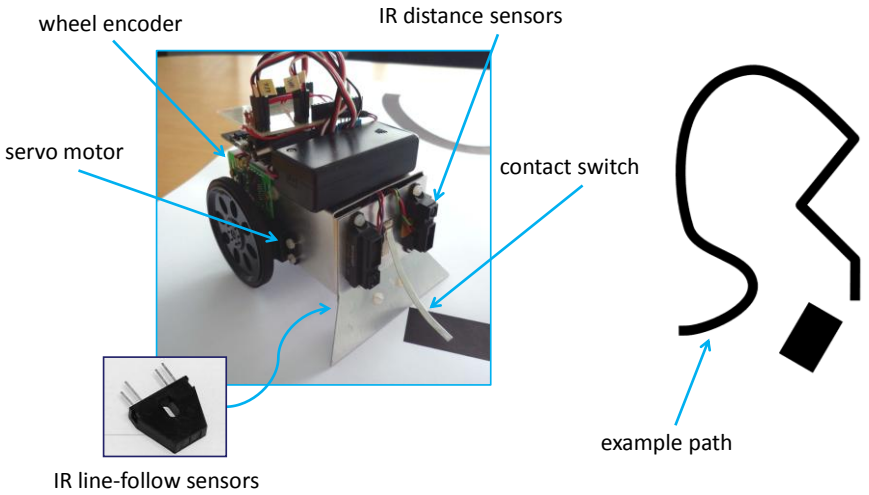
Example: Self-balancing Scooter

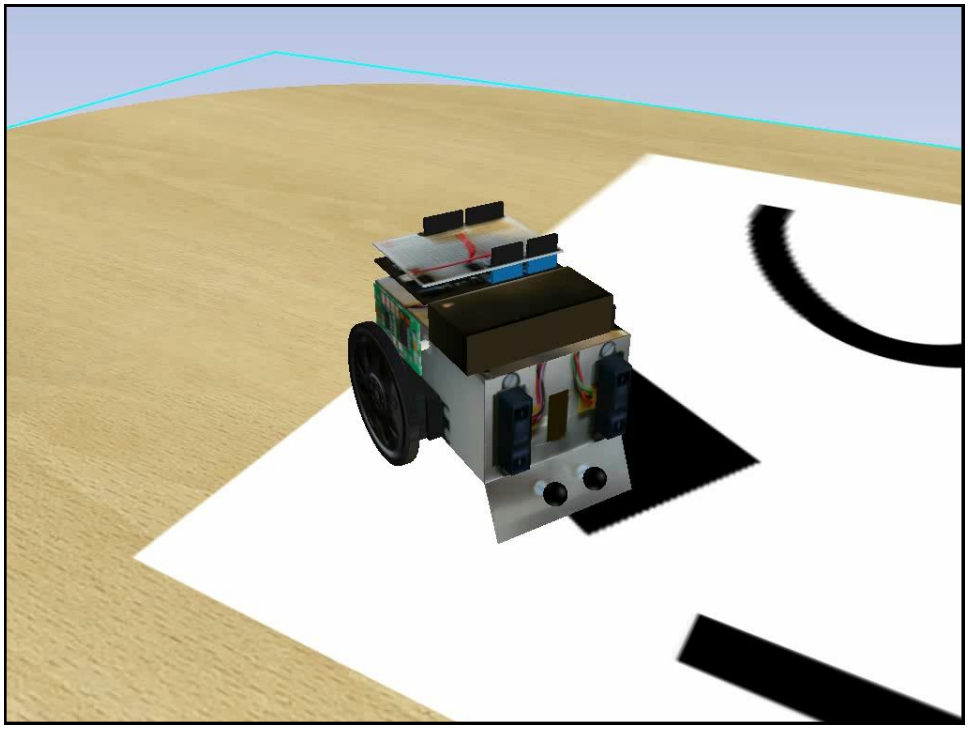




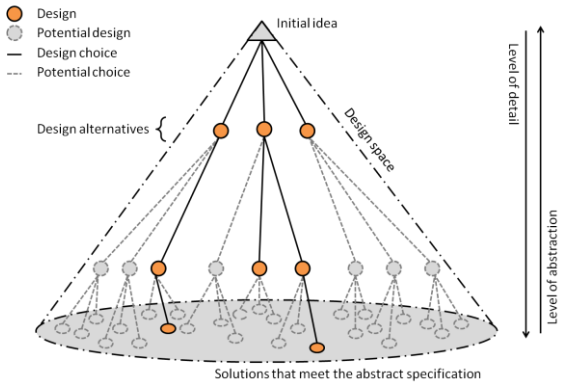
http://www.youtube.com/watch?v=pmLLGYn9Fo8

Example: Line-following Robot





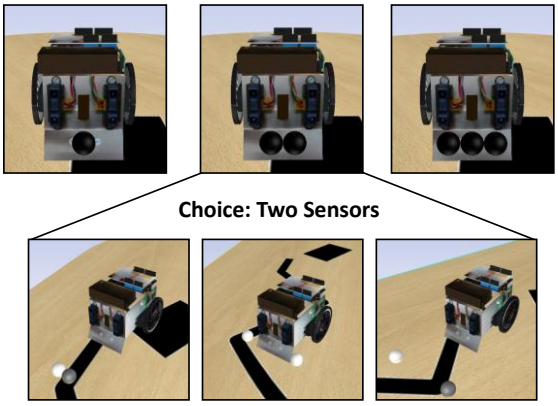
Design-Space Exploration (DSE)



- Selecting alternative designs (based on e.g. cost, performance).
- The alternative selected at each point constrains the range of designs that may be viable next steps.

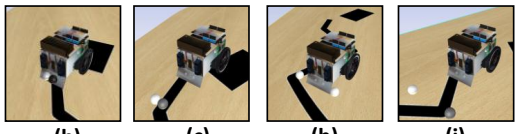
Line-following Robot DSE

- Design choices restrict the design space
- Exploration is making decisions

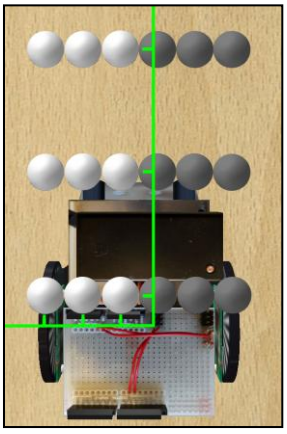


Line-following Robot DSE

		Longitudinal sensor offset		
		0.01m	**0.07m**	**0.13m**
Lateral sensor offset	**0.01m**	(a)	(b)	(c)
	0.03m	(d)	(e)	(f)
	0.05m	(g)	(h)	(i)



(b) (c) (h) (i)

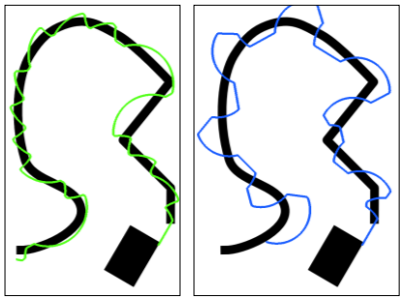


- Two parameters, 9 choices / simulations

Line-following Robot DSE

- Results can be graphical or numerical
- Designs can be evaluated by ranking functions

		Metric*				
Rank	Design	A	B	C	D	Mean Rank
1	**(b)**	**1**	**5**	**1**	**2**	**2.2**
2	(f)	7	2	4	1	3.5
3	(a)	2	8	2	4	4.0
4	(e)	3	6	3	5	4.2
5	(i)	9	1	5	3	4.5
6	(c)	5	3	6	8	5.5
7	(d)	6	4	7	7	6.0
8	(h)	4	7	8	9	7.0
9	(j)	8	9	9	6	8.0



(b) **(h)**

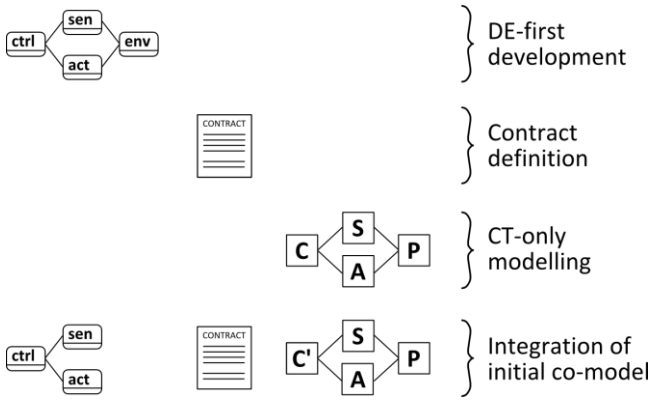
*** A = distance, B = energy, C = deviation area, D = maximum deviation**

Paths to Initial Co-models

- **DE-first**
  - initial models are produced in the discrete-event formalism; CT model added later. Focus on DE controller first.
- **CT-first**
  - Initial models are produced in the CT tool, with a DE model being introduced later to form a co-model. Focus on modelling the dynamics of the plant.
- **Contract-first**
  - Contract defined, acts as a guide. DE- and CT-models are developed separately but concurrently (DE-first and CT-first, as above). Allows for early testing of constituent models without reliance on a competent counterpart model. The constituent models are then integrated into a co-model.

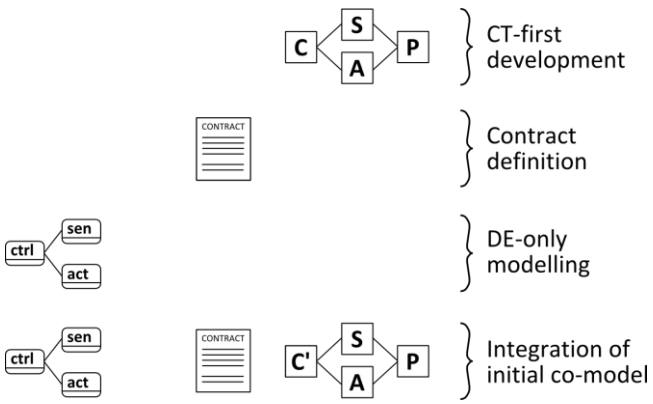
DE-first

- Initial models produced in the discrete-event formalism
- CT model added later



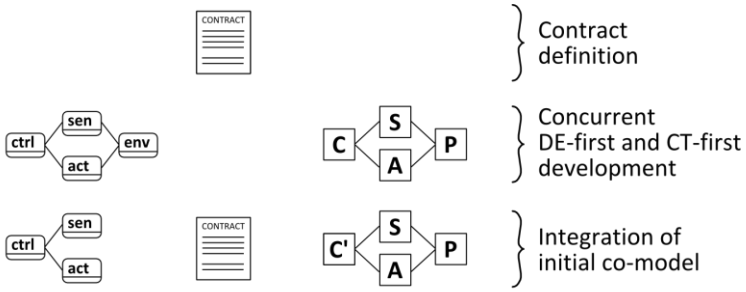
CT-first

- Initial models produced in the CT tool
- DE model introduced later to form a co-model



Contract-first

- Contract defined, acts as a guide
  - allows for early testing of constituent models
- DE- and CT-models developed separately but concurrently
  - following DE-first and CT-first as previously shown
- Constituent models are then integrated into a co-model



Choosing a Path

	Pros	Cons	Use where…
DE-first	complex controller behaviour can be studied early	plant dynamics over-simplified; loop controllers cannot be tuned; rapid increase in environment model complexity	complex DE control needs priority; legacy DE models exist; modeller experience is mainly in DE domain
CT-first	feasibility study; plant dynamics can be studied early on; loop controllers can be tuned	complex DE control cannot be easily studied	feasibility of control unknown; plant dynamics need priority; legacy CT models and/or loop controllers exist; modellers' experience is mainly in CT
Contract-first	a co-model reached early on; constituent models not mutually dependent for testing	contract required early on; extra effort is required in building testing constituent models	integration is required of two legacy models; no legacy models exist; modellers from both domains are available (or have no bias)
Other	a novel approach can fit better with existing practice	limited experience from our existing guidelines	the standard approaches do not fit your development context; legacy models / experience in other formalisms

Summary of Terms (1)

- **model**
  - a more or less abstract representation of a system or component of interest.
- **modelling**
  - the activity of creating models.
- **simulation**
  - symbolic execution of a model.
- **continuous-time simulation**
  - a form of simulation where the state of the system changes continuously through time.
- **discrete-event simulation**
  - a form of simulation where only the points in time at which the state of the system changes are represented.

Summary of Terms (2)

- **co-model**
  - a model comprising two constituent models (a DE sub-model and a CT submodel) and a contract describing the communication between them.
- **contract**
  - a description of the communication between the constituent models of a co-model, given in terms of shared design parameters, shared variables, and common events.
- **co-simulation**
  - the simulation of a co-model.
- **design space exploration (DSE)**
  - the (iterative) process of constructing co-models, performing co-simulations and evaluating the results in order to select co-models for the next iteration.

Summary

- Embedded systems design
  - requires collaborative development
  - analysis of models from different disciplines
  - diverse cultures, abstractions, formalisms
- Crescendo solution is **co-simulation**
  - combining DE models of controllers and CT models of controlled plant
  - allow existing knowledge and skill
  - enable communication between disciplines