Can robots ever be safe?
Software Engineering of Robots

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Software Engineering of Robots: why are we interested?

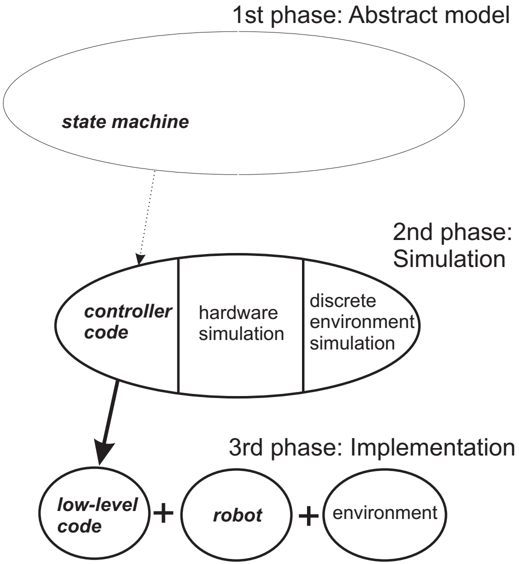
- One of UK eight great technologies: robotics and autonomous systems.
- £13 billion global market predicted for 2025
- Safety: numerous applications of concern
- Autonomous vehicles
- Home automation
- Full verification is beyond the state of the art
- Among other concerns: verification of controller software

Software Engineering of Robots

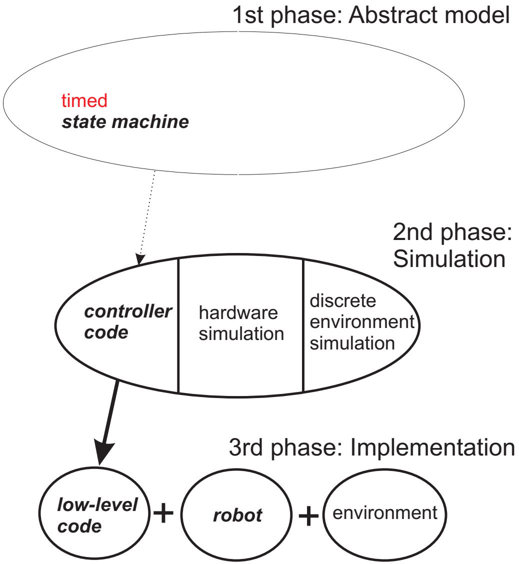
- ASV: Unmanned Marine Systems, Rich Daltry
- Blue Bear Systems, Yoge Patel
- Bristol Robotics Laboratory, Alan Winfield
- Centre for Autonomous Systems Technology, Michael Fisher
- D-RisQ, Nick Tudor
- Flightworks, Matt Pilmoor
- IBM Ireland, Patrick O'Sullivan
- Tekever, Mark Baxter

Outline

Current approach to development



What do we want to do?



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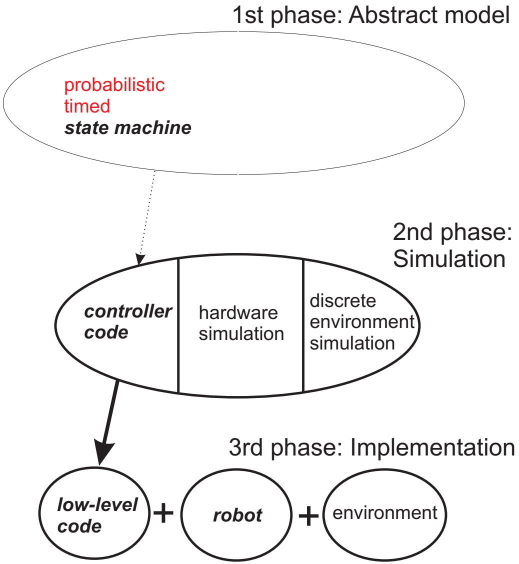

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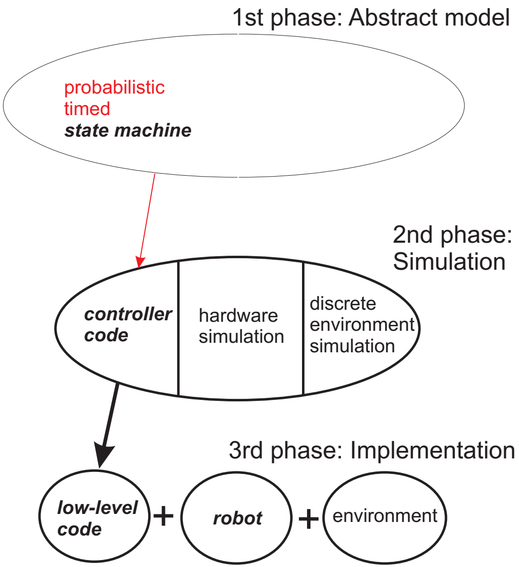

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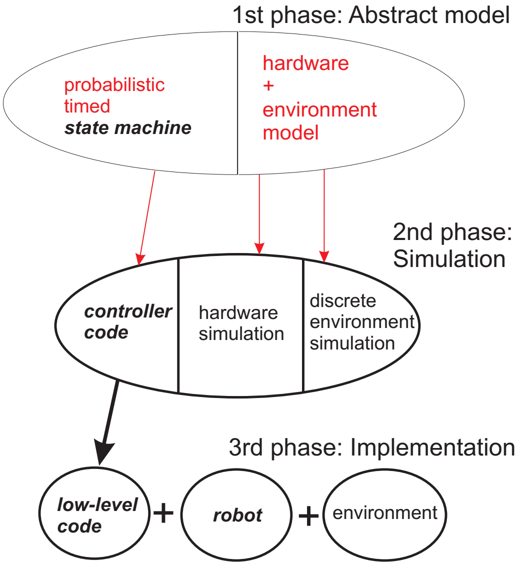

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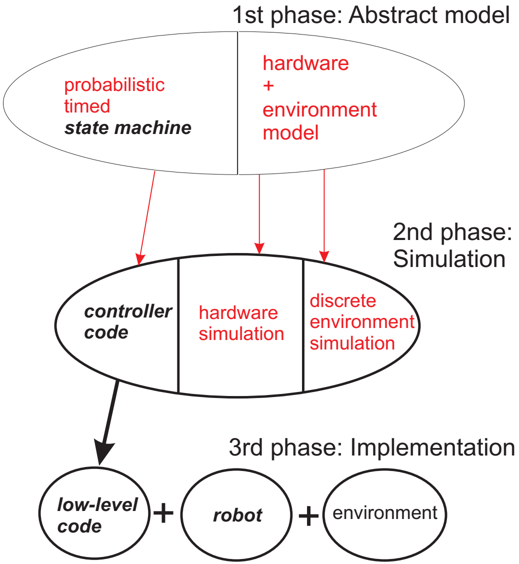

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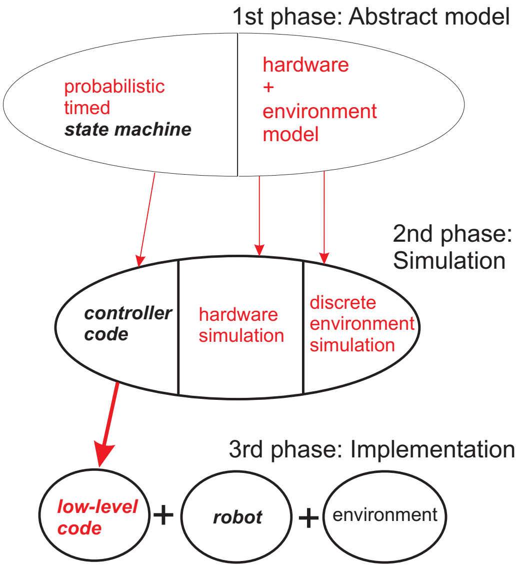
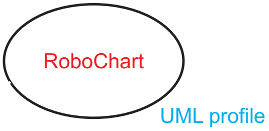

1st phase: Abstract model
probabilistic timed state machine
hardware + environment model
2nd phase: Simulation
controller code
hardware simulation
discrete environment simulation
3rd phase: Implementation
low-level code
+
robot
+
environment

How do we want to do it?



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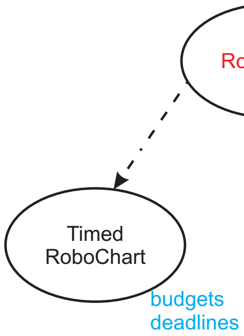

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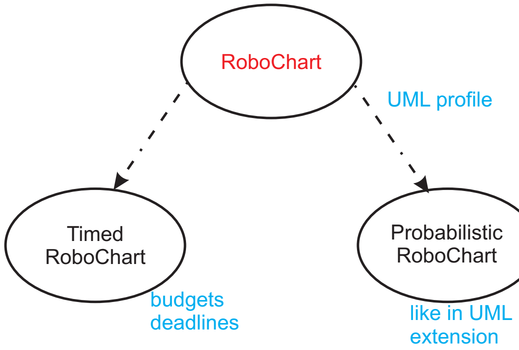

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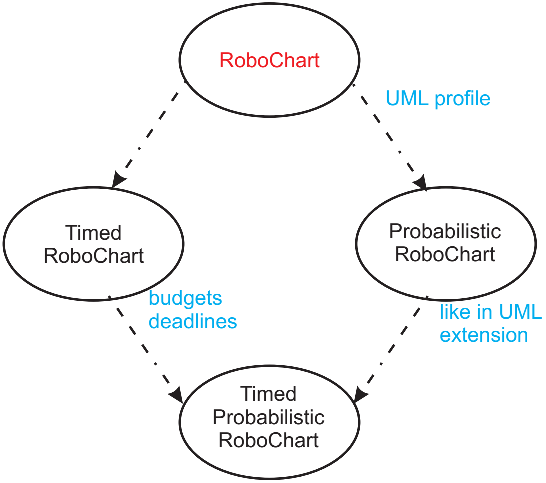

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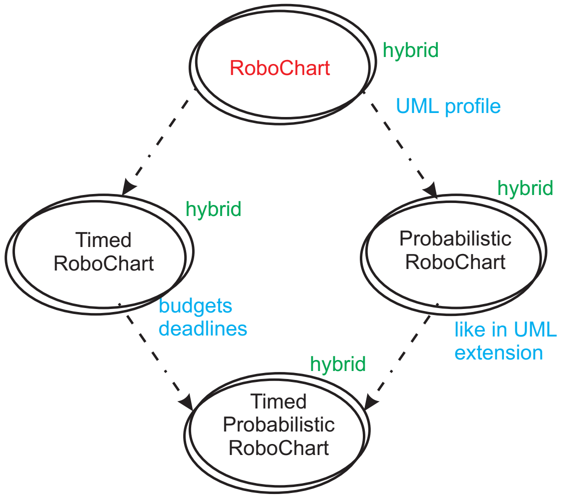
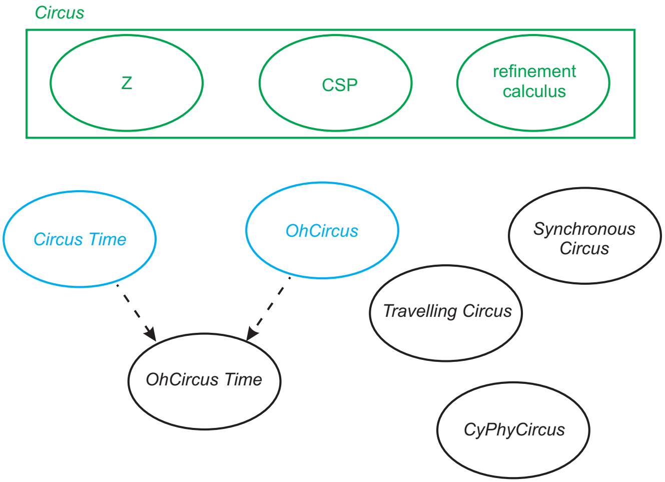
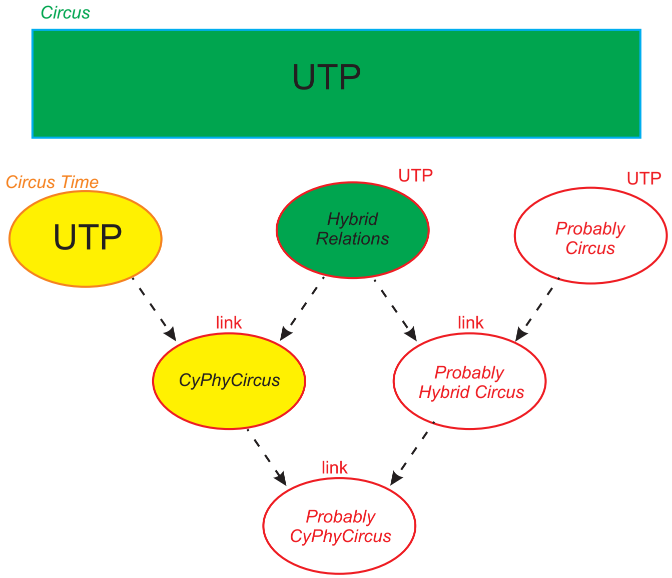


Behind the scenes: it's a *Circus*



Brought to you by the UTP



RoboChart: why a new notation?

Requirements from robotics

- **Architecture**
  Specific architectural pattern adopted in robotic systems
- **System**
  Clear identification of system
- **API**
  Capture common operations for common functions and kinds of equipment
- **Time and probability**
  Primitives to specify time budgets, deadlines, and probabilities

RoboChart: why a new notation?

Requirements from verification

- **Constraints** Constrained usage to simplify semantics and enable efficient verification
- **Compositional** Encourage component-based modelling to foster compositional reasoning
- **Language** Well defined language constructs with a fixed syntax and semantics
- **Refinement** Refinement-based semantics to support proof of correctness of simulations

RoboChart: chemical detector

Overall behaviour

- Search for chemical spills
- Approach
- Drop flag
- Continue

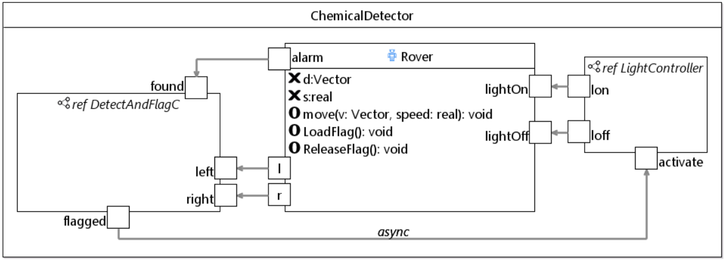
Video

Module

Identifies a robotic system

- Models a single robot
- One Robotic Platform
- One or more Controllers
- Communication
  - Synchronous
  - Asynchronous
- Robotic Platform may provide shared variables

Chemical Detector: Module



- Links controller DetectAndFlagC and LightController to Rover
- Rover records assumptions about the hardware
- DetectAndFlagC and LightController interact asynchronously

Robotic Platform

- Records assumptions about the hardware
  - which events the hardware provides
  - which events the hardware accepts
  - which operations the hardware supports
  - which variables are available
- Independent of controller and state-machines
- Defines a module when composed with one or more controllers
- Single point of interaction with environment

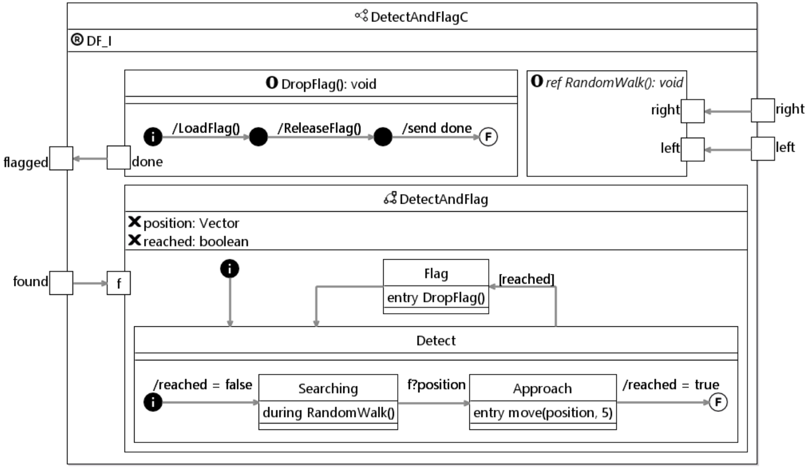
Controller

- Models a specific behaviour
- Contains:
  - Behavioural state-machines
  - Operations
  - Variables
  - Events
- Supports multiple behavioural state-machines
- Communication between state-machines is synchronous

Chemical Detector: DetectAndFlagC

- Three state-machines
  1. Operation Definition – DropFlag()
  2. Operation Reference – *ref RandomWalk()*
  3. Behaviour Definition – DetectAndFlag
- All communication is synchronous
- Interface DF_I records assumptions:
  - input events – found, right and left
  - output events – flagged
  - available operations – move, LoadFlag, ReleaseFlag
- Behaviour state-machine records:
  - position of detected chemical spill
  - status of approach action

Chemical Detector: DetectAndFlagC



State Machines

Main behavioural specification constructs

- Simple, composite and final states
- Initial and junction nodes
- Actions: entry, during, exit, transition
- Local variables
- Action language: assignments, events, operation calls, sequential composition

Exclusions

- No interlevel transitions
- No history junctions
- No parallel regions
- No inner transitions

Extra constructs

- Types based on Z Mathematical Toolkit
- Interfaces: grouping variables, events, operations
- API
    - Common operations
    - State machines
    - Pre and postconditions
    - Grouped in packages
    - Default simulation

Semantics: Overview

Core notation

- Formalised in CSP, for now, for the core notation
- *Circus* and UTP in the long term
- *Semantics for refinement*
- Module = CSP Process
    - Parallel composition of controllers
    - Connections define synchronisation sets
    - Asynchronous communication modelled through buffers
- Controller = CSP Process
    - Parallel composition of state machines
    - Connections define collaborations via events
- State machine = CSP process
    - Parallel composition of states
    - Connections define flow of transitions

Semantics: Overview

Challenges

- Simplicity
- Compositionality

Our compromise

- Transitions are part of the source states
- Junctions are part of the incoming transition
- Initial nodes and final states are part of the parent state
- States interact with each other to enter and exit
- States synchronise on transition triggers to support top-down interruption
- State components isolated in memory process due to sharing

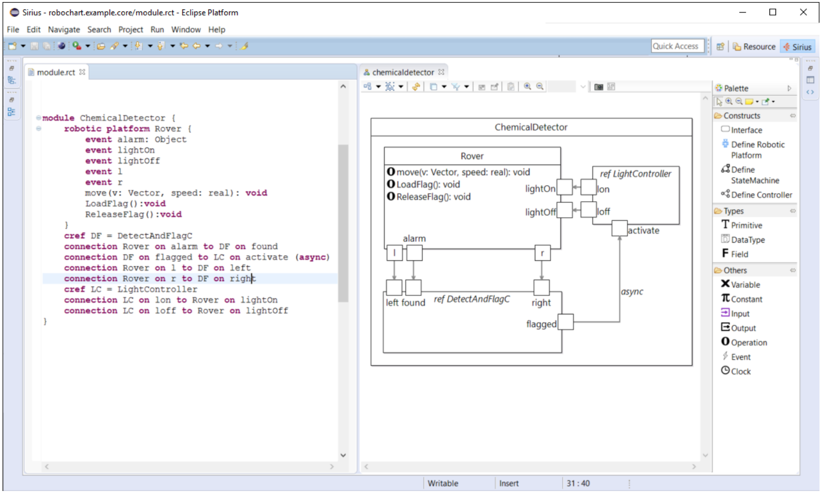
RoboTool

- Eclipse plugins
- Code generator for subset of the semantics
- Validation rules

Validation

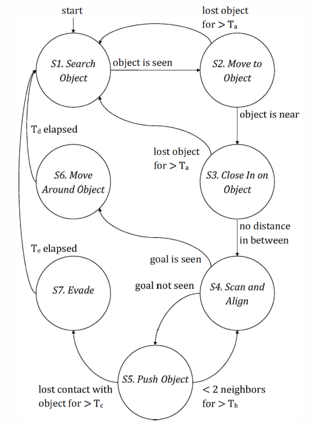
- Chemical Detector and other examples
- Generated semantics used for verification using FDR3
- Large state-space for simple state-machines
- *FDR3 compression functions highly effective*

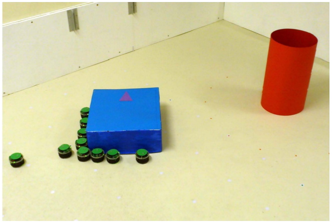
RoboTool: short demonstration



```
module ChemicalDetector {
    robotic platform Rover {
        event alarm: Object
        event lightOn
        event lightOff
        event l
        event r
        move(v: Vector, speed: real): void
        LoadFlag():void
        ReleaseFlag():void
    }
    cref DF = DetectAndFlagC
    connection Rover on alarm to DF on found
    connection DF on flagged to LC on activate (async)
    connection Rover on l to DF on left
    connection Rover on r to DF on right
    cref LC = LightController
    connection LC on lon to Rover on lightOn
    connection LC on loff to Rover on lightOff
}
```

Timed Models





"A group of e-puck robots transporting an object (blue box) towards a goal (red cylinder)."

Jianing Chen, M. Gauci and R. Gross. "A strategy for transporting tall objects with a swarm of miniature mobile robots". In: Robotics and Automation (ICRA), 2013 IEEE International Conference on. 2013, pp. 863869.

Timed Models

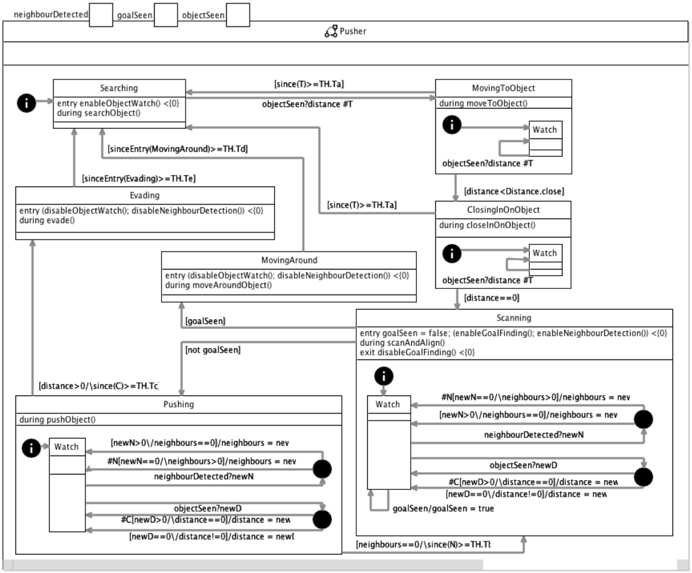
Requirements

- Reasoning about time
- Time budgets
- Time deadline

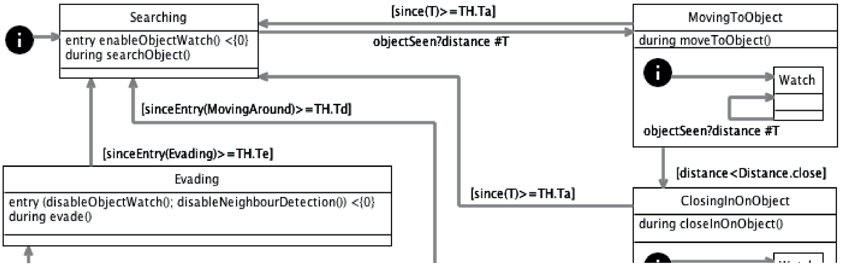
Main design decisions

- Operations take 0 time
- Budget: wait(t)
- Deadline: S $<\{d\}$
- Simple clocks based on states and transitions.

Timed Language


neighbourDetected
goalSeen
objectSeen
Pusher
Searching
entry enableObjectWatch() <{0}
during searchObject()
[since(T)>=TH.Ta]
objectSeen?distance #T
MovingToObject
during moveToObject()
Watch
objectSeen?distance #T
[sinceEntry(MovingAround)>=TH.Td]
[sinceEntry(Evading)>=TH.Te]
Evading
entry (disableObjectWatch(); disableNeighbourDetection()) <{0}
during evade()
[since(T)>=TH.Ta]
[distance<Distance.close]
ClosingInOnObject
during closeInOnObject()
Watch
objectSeen?distance #T
MovingAround
entry (disableObjectWatch(); disableNeighbourDetection()) <{0}
during moveAroundObject()
[distance==0]
[goalSeen]
Scanning
entry goalSeen = false; (enableGoalFinding(); enableNeighbourDetection()) <{0}
during scanAndAlign()
exit disableGoalFinding() <{0}
[not goalSeen]
[distance>0/\since(C)>=TH.Tc
Pushing
during pushObject()
Watch
[newN>0\/neighbours==0]/neighbours = nev
#N[newN==0/\neighbours>0]/neighbours = nev
neighbourDetected?newN
objectSeen?newD
#C[newD>0/\distance==0]/distance = new
[newD==0\/distance!=0]/distance = newI
Watch
#N[newN==0/\neighbours>0]/neighbours = nev
[newN>0\/neighbours==0]/neighbours = nev
neighbourDetected?newN
objectSeen?newD
#C[newD>0/\distance==0]/distance = new
[newD==0\/distance!=0]/distance = new
goalSeen/goalSeen = true
[neighbours==0/\since(N)>=TH.Tt

Timed Language



Timed semantics

Current status

Conservative discrete-time extension of the untimed semantics.

- Specified using constructs of Timed CSP/*CircusTime*
- Translated to tock-CSP for model checking of interesting properties
- Translation to UPPAAL also of interest

Timed semantics

Current assumptions

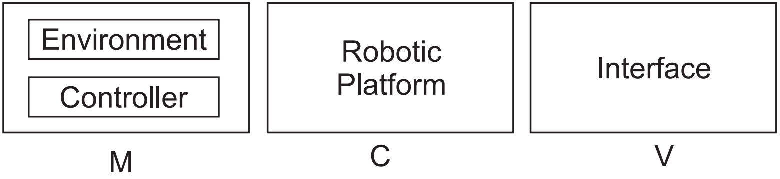
- Conjunctive conditions.
- No program variables compared with $\mathit{since}(C)$ or $\mathit{sinceEntry}(S)$.
- No more than one clock compared in the same expression.

These can likely be relaxed, however, the semantic model becomes more complicated, and potentially less compositional.

And now to simulations and programs

RoboSim

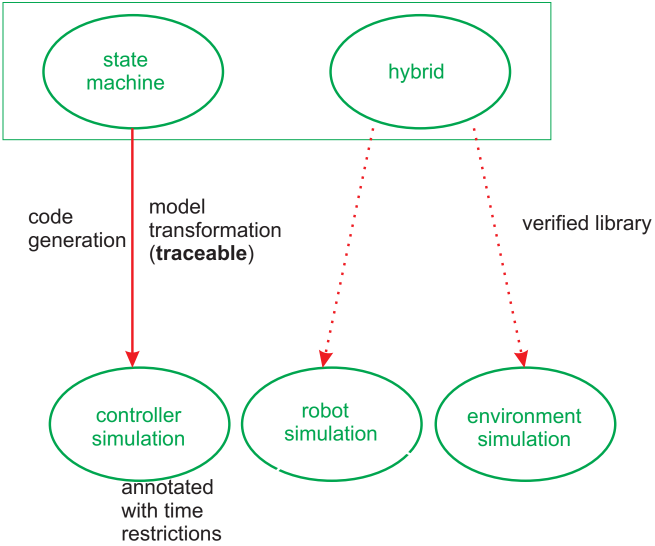
- General: high-level and tool independent
- For use with a variety of tools
    - simulating different kinds of robots
    - including different scenarios



RoboSim

- Automatically generated
- Guaranteed to be sound

But how can we handle the robot and the environment?



Co-simulation

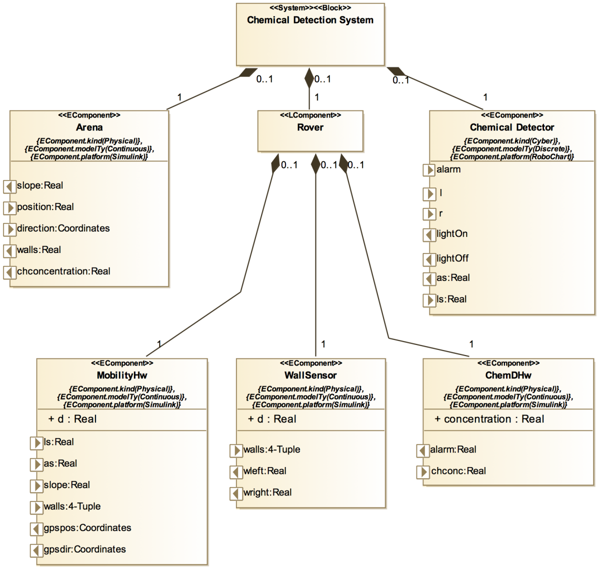
Technique that deals with the increased complexity via the coordinated use of heterogeneous models and tools. An industry standard, FMI, supports orchestration.

SysML Profile

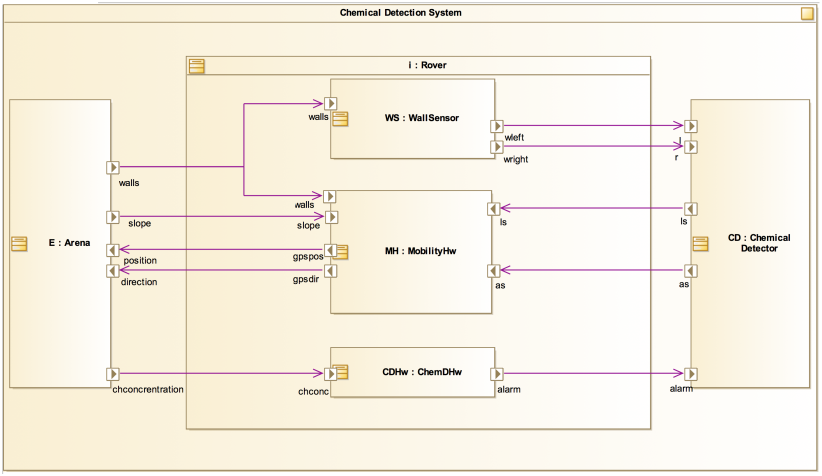
RoboChart models with other notations:

- Simulink
- Modelica
- VDM
- . . .

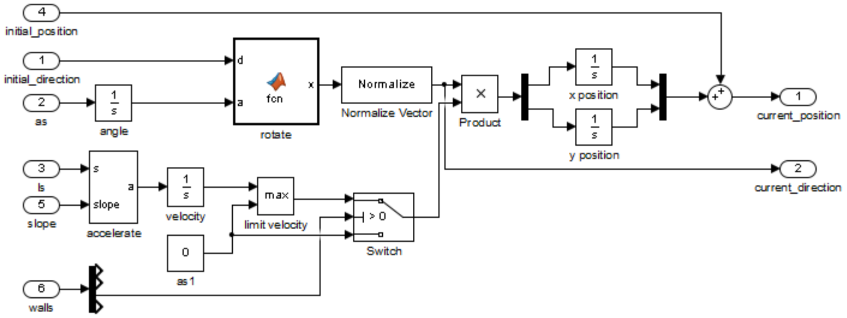
Co-simulation: Architecture Structure Diagram


<<System>><<Block>>
Chemical Detection System
0..1
0..1
0..1
1
1
1
<<EComponent>>
Arena
{EComponent.kind(Physical)},
{EComponent.modelTy(Continuous)},
{EComponent.platform(Simulink)}
slope:Real
position:Real
direction:Coordinates
walls:Real
chconcentration:Real
<<LComponent>>
Rover
0..1
0..1
0..1
<<EComponent>>
Chemical Detector
{EComponent.kind(Cyber)},
{EComponent.modelTy(Discrete)},
{EComponent.platform(RoboChart)}
alarm
l
r
lightOn
lightOff
as:Real
ls:Real
1
1
1
<<EComponent>>
MobilityHw
{EComponent.kind(Physical)},
{EComponent.modelTy(Continuous)},
{EComponent.platform(Simulink)}
+ d : Real
ls:Real
as:Real
slope:Real
walls:4-Tuple
gpspos:Coordinates
gpsdir:Coordinates
<<EComponent>>
WallSensor
{EComponent.kind(Physical)},
{EComponent.modelTy(Continuous)},
{EComponent.platform(Simulink)}
+ d : Real
walls:4-Tuple
wleft:Real
wright:Real
<<EComponent>>
ChemDHw
{EComponent.kind(Physical)},
{EComponent.modelTy(Continuous)},
{EComponent.platform(Simulink)}
+ concentration : Real
alarm:Real
chconc:Real

Co-simulation: Connection Diagram



Co-simulation: A Simulink Diagram



Co-simulation: A UTP-based FMI semantics

- We have a CSP semantics for FMI.
- Only one cyber component: with RoboChart semantics
- We need a timed simulation semantics
- Variables become channels: output ports
- Operations are hidden
- Specification for FMI simulations
    - Verification of master algorithms
    - Hybrid reasoning
- Extension to FMI: treatment of events

So, can robots be safe?

A lot to do

- Computer vision, artificial intelligence, human-robot interaction, ethics, ...
- Software Engineering
- Theory: UTP
- Practice: new languages (formal, diagrammatic, API)
- Verification: compositional, scalable, traceable

Our distinctive vision

- Notations akin to those already used
- Sound integration
- Full life cycle

The theory is that of cyber-physical systems.