Using model checking to improve the quality of cyber-physical systems

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Cyber-Physical Systems

Cyber-Physical Systems or "smart" systems are co-engineered interacting networks of physical and computational components. – NIST

Examples

- Smart grid
- Autonomous automotive systems
- Medical monitoring
- Robotics

Networks of embedded systems with physical input and output

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Modelling and analysis of cyber-physical systems

Two types of behaviour in CPS:

- Continuous dynamics
- Discrete dynamics

This talk: discrete dynamics

Case study 1: IEEE 11073-20601

INTERNATIONAL STANDARD

ISO/IEEE 11073-20601

First edition
2010-05-01

Health informatics — Personal health device communication —

Part 20601:
Application profile — Optimized exchange protocol

Informatique de santé — Communication entre dispositifs de santé personnels —

Partie 20601: Profil d'application — Protocole d'échange optimisé

Reference number
ISO/IEEE 11073-20601:2010(E)

Continua HEALTH ALLIANCE

and many more

What are personal health devices?

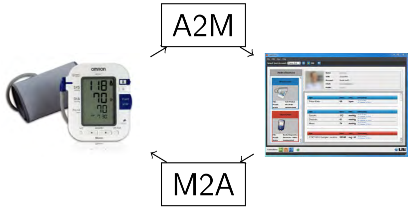
Agent devices

Manager devices

What is the purpose of IEEE 11073-20601?

"[. . .] define[. . .] a common framework for making an abstract model of personal health data available in transport-independent transfer syntax required to establish logical connections between systems and to provide presentation capabilities and services needed to perform communication tasks." [IEEE std 11073-20601]

Protocol (sketch)



Agent and manager cycle through states:

- Unassociated
- Associating
- Sending configuration
- Waiting approval
- OperatingOperating
- Disassociating

Objectives & Approach

- Assess understandability, consistency, and completeness
  - Formalise protocol in mCRL2 (ACP-like process algebra)
  - Based on standards document
- Establish correctness
  - Formulate desired properties in temporal logic (μ-calculus)
  - Use model checker to verify the properties
- Fix bugs

Observations on the standard

Understandability, consistency and completeness

- Requirements are not explicit
- Formalisms not introduced
- Information inconsistently duplicated between representations
  - Inconsistent terminology/abbreviations
  - Different state changes for same event
- Unexpected messages not fully treated

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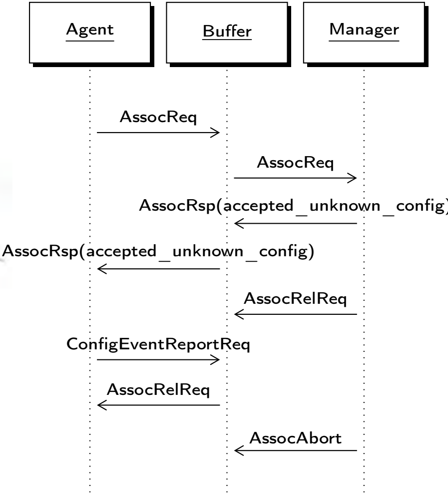
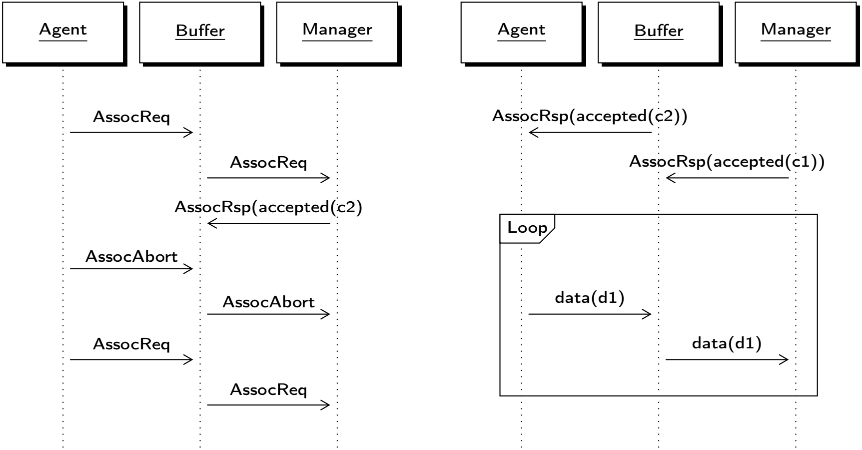
Deadlocks caused by incompleteness



Correctness

Data shall not be transmitted in inconsistent operating states.



Observations

- Omissions and inconsistencies cause easy to fix bugs
- Session setup contains a severe bug
- Agent and manager devices can transfer data in inconsistent configurations
- Rest of the protocol should be verified

Lessons learned

- Formal modelling allows detection of problems in short timespan
- Standards should provide clear requirements
- Bugs cannot be fixed without breaking standard conformance
- Formal verification should be part of the development process of every communication standard

Unverified standards contain subtle, hard to find errors!

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Case study 2: CERN

source: CERN

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Large Hadron Collider

source: CERN

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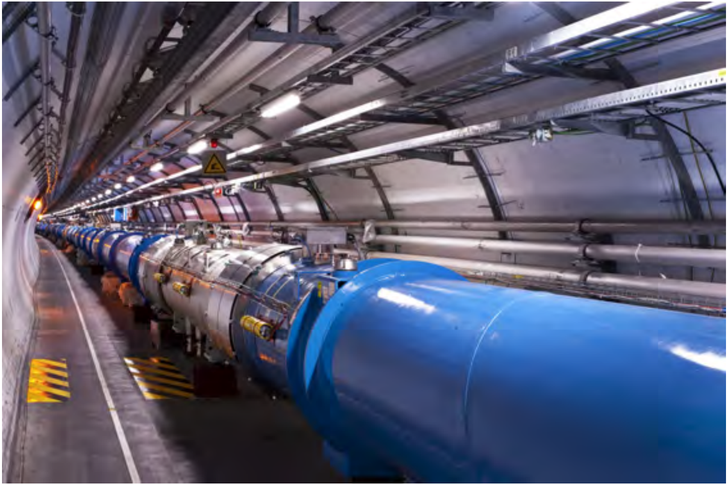
Large Hadron Collider



source: CERN

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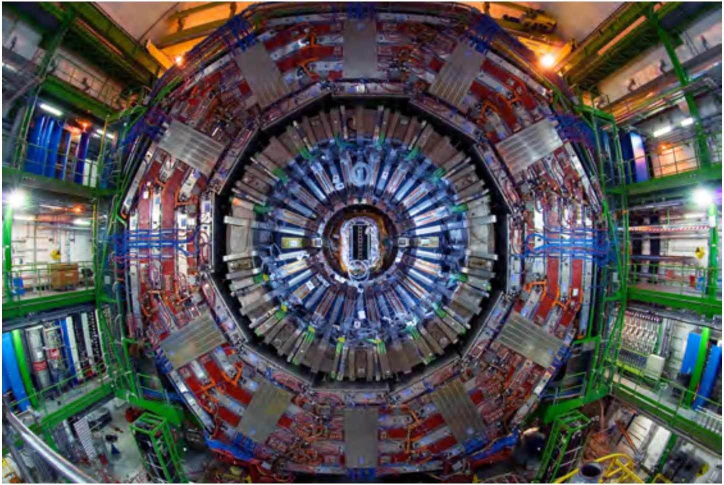
CMS



source: CERN

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CMS detector: Scale

source: CERN

Control software

source: CERN

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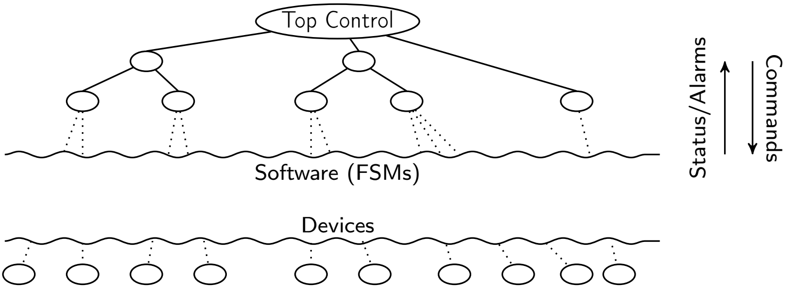
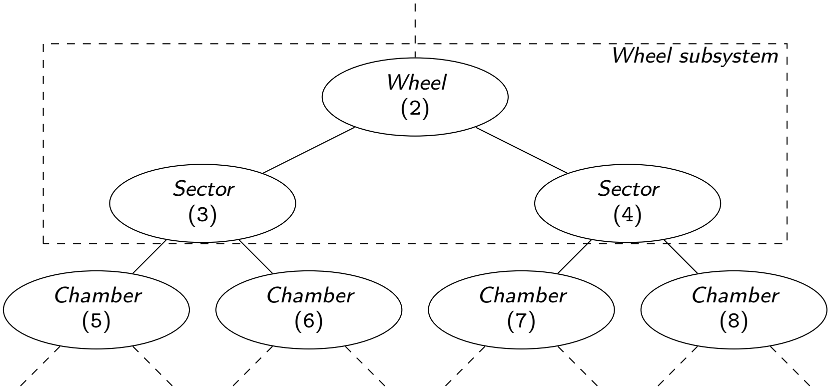
Control software: Global structure



Control software: Local structure



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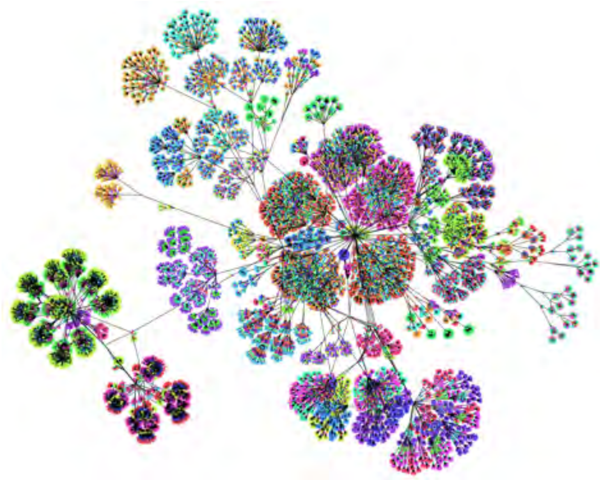
Control software: Complexity



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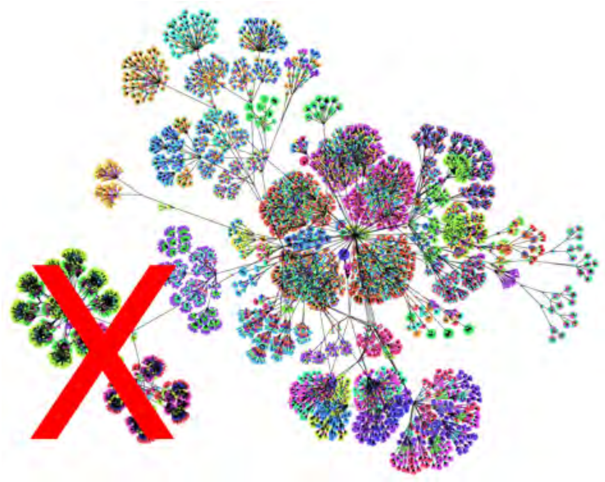
Problem: Unresponsive subsystems



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Methodology

1. Understand/define semantics SML
2. Identify desirable properties
3. Verify properties
4. Automate verification
5. Optimise verification (dedicated tooling)
6. Integrate tooling into IDE

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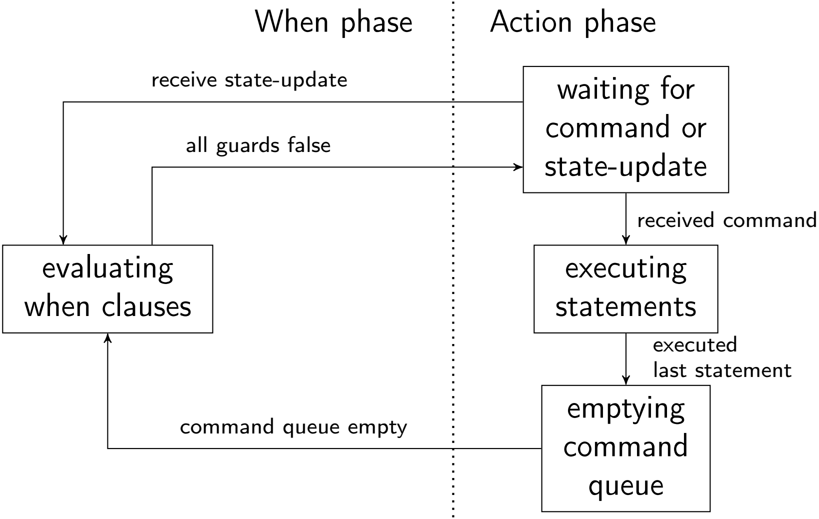
State manager language

Example (SML)

```
class: $FWPART_$TOP$RPC_Chamber_CLASS
  state: OFF
    when (($ANY$FwCHILDREN in_state ERROR) or
          ($ANY$FwCHILDREN in_state TRIPPED))
          move_to ERROR
    ...

    action: STANDBY
      do STANDBY $ALL$RPC_HV
      do ON $ALL$RPC_LV
```

Processing in a state machine



Stabilisation: Livelocks

```
state: ANALOG_ON_RED
 ...
 when ( $ANY$TkPowerGroup not_in_state
        DIGITAL_ON_RED )
      move_to LVMIXED
 ...
state: LVMIXED
 ...
 when ( $ALL$FwCaenChannelCtrl in_state ON  and
        $ALL$TkPowerGroup in_state ANALOG_ON_RED )
      move_to ANALOG_ON_RED
 ...
```

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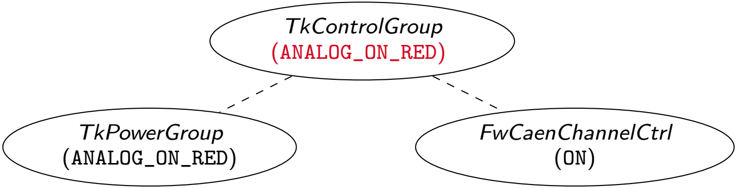
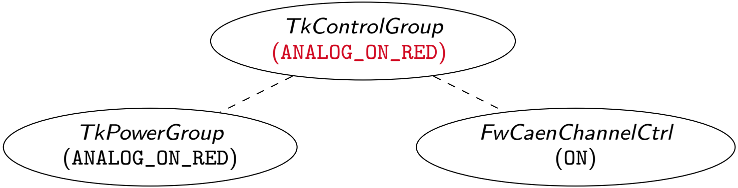
Stabilisation



Stabilisation




```
state: ANALOG_ON_RED
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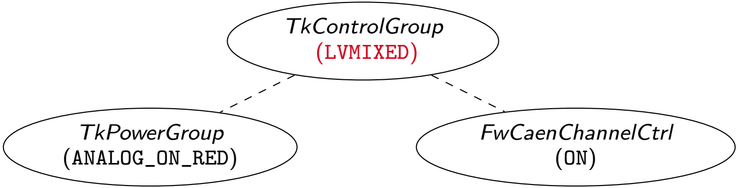
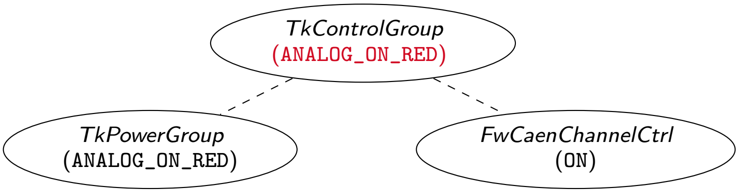
Stabilisation




```
state: LVMIXED
 ...
 when ( $ALL$FwCaenChannelCtrl in_state ON  and
        $ALL$TkPowerGroup in_state ANALOG_ON_RED )
      move_to ANALOG_ON_RED
 ...
```

Stabilisation




```
state: ANALOG_ON_RED
...
when ( $ANY$TkPowerGroup not_in_state
       DIGITAL_ON_RED )
     move_to LVMIXED
...
```

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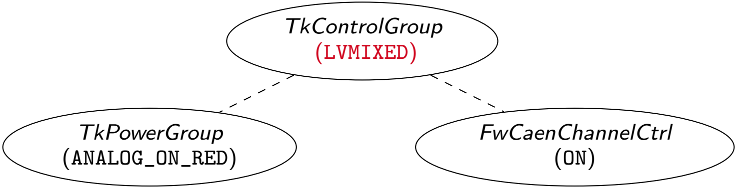
Stabilisation

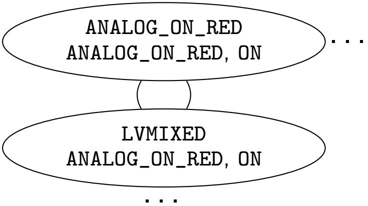



```
state: LVMIXED
 ...
 when ( $ALL$FwCaenChannelCtrl in_state ON  and
        $ALL$TkPowerGroup in_state ANALOG_ON_RED )
      move_to ANALOG_ON_RED
 ...
```

Livelocks

Formalisation

$$\mathcal{F} + children \rightarrow \mathcal{M}$$



Lemma

$\mathcal{F}$ contains a loop of $move\_to$ actions iff $\mathcal{M}$ contains loops

Livelocks

Translation to SAT

Existence of loop in $\mathcal{F}$ as satisfiability formula $\varphi_{\mathcal{F}}$:

1. state constraints
   - each FSM is always in exactly one state
   - children do not change state in when-phase
2. transition relation
   - move-to steps parents can take
3. loop condition
   - parent must be able to return to its starting state

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Livelocks

Translation to SAT

Theorem

There is a loop in $\mathcal{F}$ iff $\varphi_{\mathcal{F}}$ is satisfiable

SAT encoding will find child states if loop exists!

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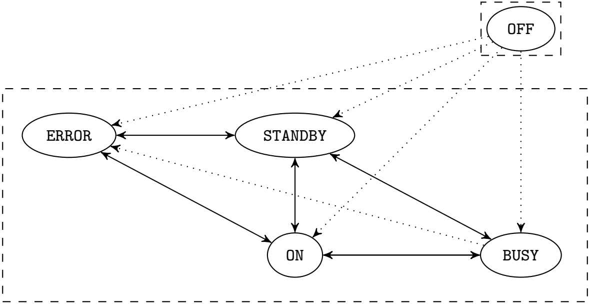
Results: Livelocks

- Full system checking in 79 seconds
- 1 302 FSMs have looping potential
- Most not observed/short lived
- Outages of control system traced back to detected problems:

```
...
6/11/2011 15:23:57 - [PIXELBARREL_BMI_S7] in state [ANALOG_ON_RED]
6/11/2011 15:23:57 - [PIXELBARREL_BMI_S7] in state [LVMIXED]
6/11/2011 15:23:57 - [PIXELBARREL_BMI_S7] in state [ANALOG_ON_RED]
...
6/11/2011 15:38:08 - [PIXELBARREL_BMI_S7] in state [ANALOG_ON_RED]
6/11/2011 15:38:08 - [PIXELBARREL_BMI_S7] in state [LVMIXED]
6/11/2011 15:38:08 - [PIXELBARREL_BMI_S7] in state [ANALOG_ON_RED]
6/11/2011 15:38:08 - [PIXELBARREL_BMI_S7] in state [LVMIXED]
...
```

Unreachable states

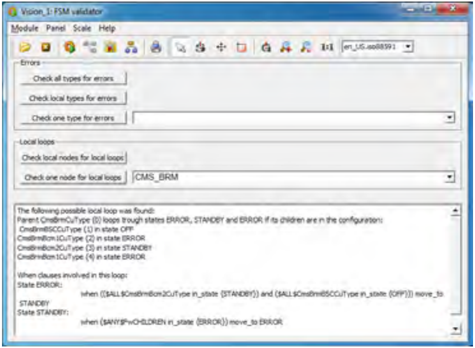


Results: Reachability

- Full system checked in 18 minutes
- 903 FSMs have reachability issues
- Partly due to clever programmer tricks
- Real problems typically due to copy/paste

Implementation

- Full automated translation to mCRL2
- Dedicated translations to SMT for described problems
- Integration of dedicated tools in IDE



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Lessons learned

- Generic tools needed to develop understanding
- Huge system, yet verifiable due to careful analysis
- Specialised tools needed for effective verification
- Real-life problems detected
- Diagnostics ensure quick fixing

"We should have had these tools at the start of the LHC project" — CMS engineer

Verification of Cyber Physical Systems

Cyber physical systems

Networks of embedded systems with physical input and output

- Modelling and verification well-understood
- Possible for huge systems

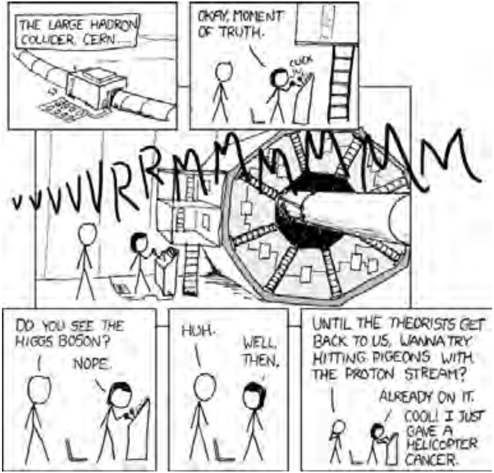
- Modelling and verification using differential equations
- Well-studied

- Combining discrete- and continuous dynamics in single formalism
- Modelling and verification using: hybrid automata
- Currently studying this with Prof. Cleaveland

Thank you

Joint work with:

- Martijn Klabbers (LaQuSo)
- Yi Ling Hwong (CERN)
- Vincent Kusters (TU/e, CERN, ETH-Z)
- Sander Leemans (TU/e, CERN)
- Tim Willemse (TU/e)



source: `http://xkcd.com/401`

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