Verifying and Monitoring UML Models with Observer Automata

A Transformation-free Approach

ACM/IEEE 22th International Conference on Model Driven Engineering Languages and Systems (MODELS'19) in Munich, Germany

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Context

Observations

- Increasing complexity and connectivity of embedded systems
  - ⇒ Increasing exposure to potential software failures
  - ⇒ Increasing difficulty to detect, understand, and fix software failures

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- Testing or proving that a system satisfies its expected properties
  - Possibly relying on environment abstractions
    (inputs to consider and execution platform)

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- Testing or proving that a system satisfies its expected properties
  - Possibly relying on environment abstractions (inputs to consider and execution platform)

Need for runtime monitoring

- Detecting safety property violations at runtime (with the actual environment)
- Making it possible to trigger safe system recovery procedures

Overview

Goal

Provide a technique to execute models on embedded targets with facilities to perform model-checking and runtime monitoring on these models

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Our previous work [Besnard et al., MODELS 2018]

1. Identified problems on classical **model-checking** approaches
2. Introduced a solution based on a model interpreter

Overview

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Provide a technique to execute models on embedded targets with facilities to perform model-checking and runtime monitoring on these models

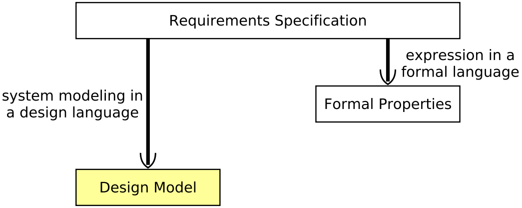
Our previous work [Besnard et al., MODELS 2018]

1. Identified problems on classical **model-checking** approaches
2. Introduced a solution based on a model interpreter

In this work

3. Identify problems on classical **monitoring** approaches
4. Can we address these problems with the model interpreter approach?

(1) Classical Approach with Model-checking



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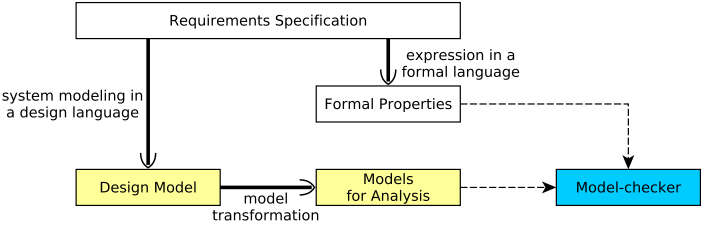

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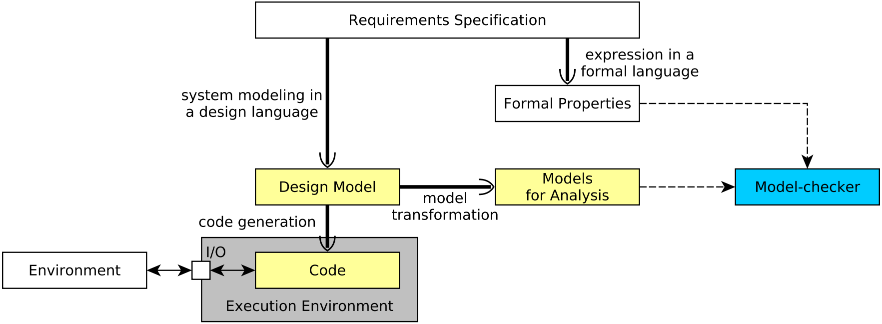

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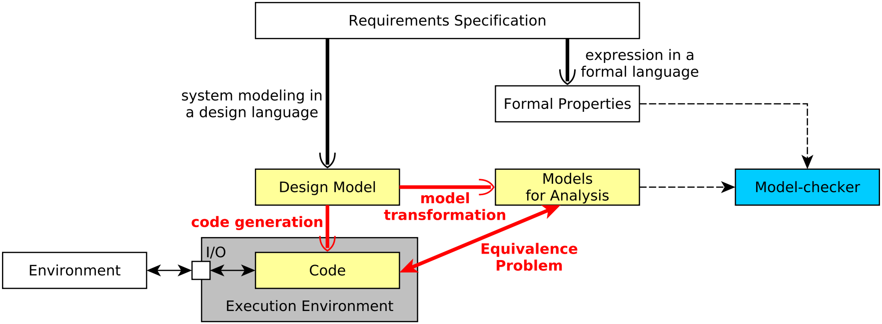
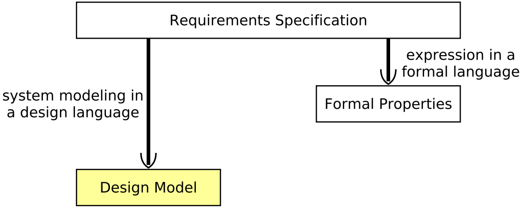


Problems: Two semantic gaps and an equivalence problem caused by transformations of the design model into different languages

(2) Our Approach with Model-checking [Besnard et al., MODELS 2018]



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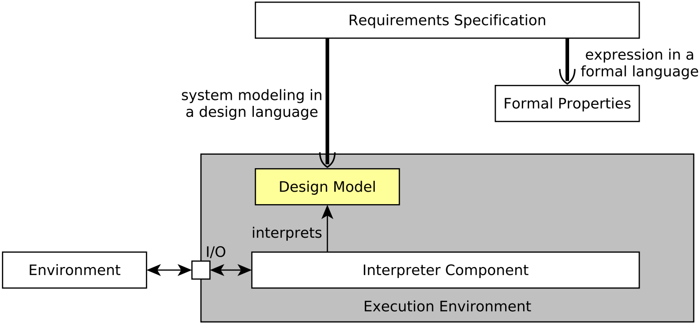

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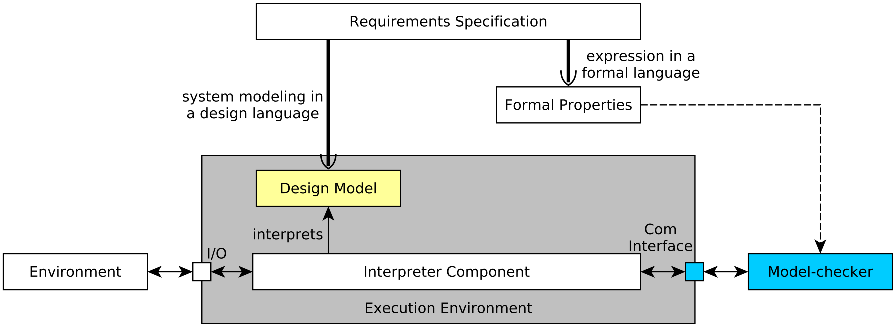
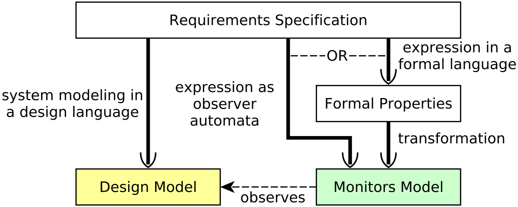


A unique definition of the language semantics
for verification activities and model execution

(3) Classical Approach with Monitoring



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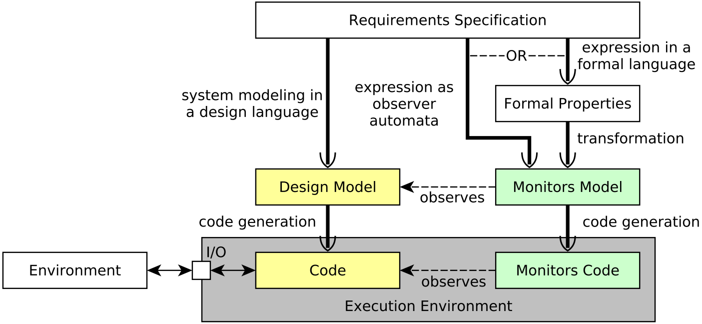

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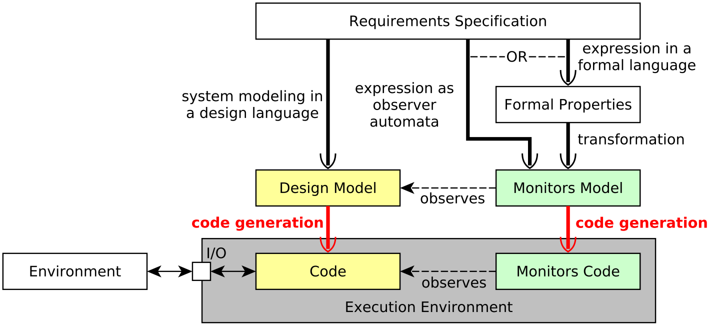

1. Semantic gap between monitors model and monitors code

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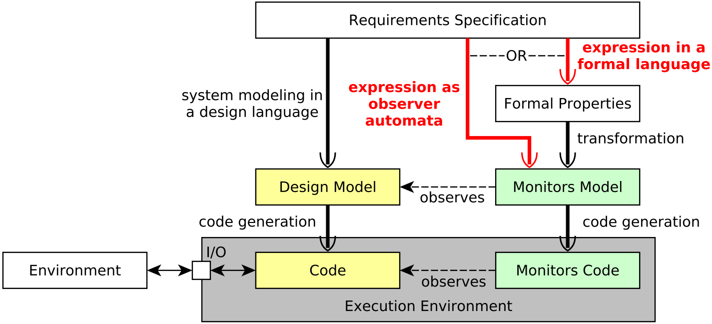

1. Semantic gap between monitors model and monitors code
2. Languages used to express monitors and design models are usually different

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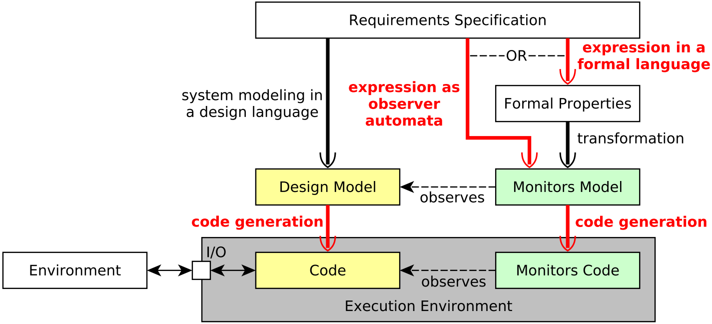

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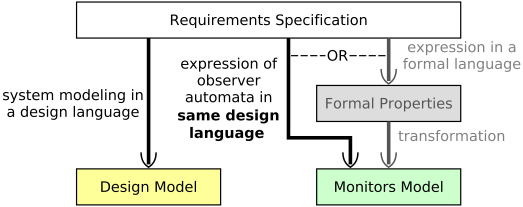

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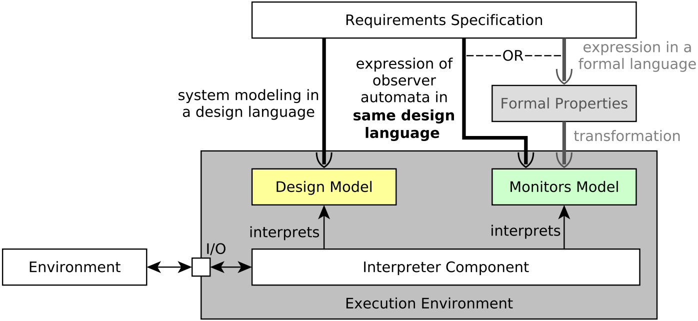

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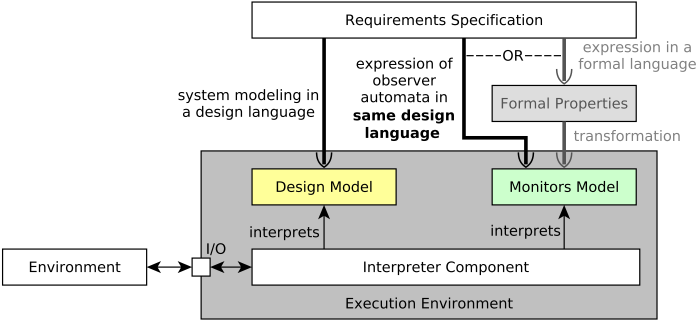

The same component interprets both design and monitors models:

1. No semantic gap
2. Only one language to express system and monitors models

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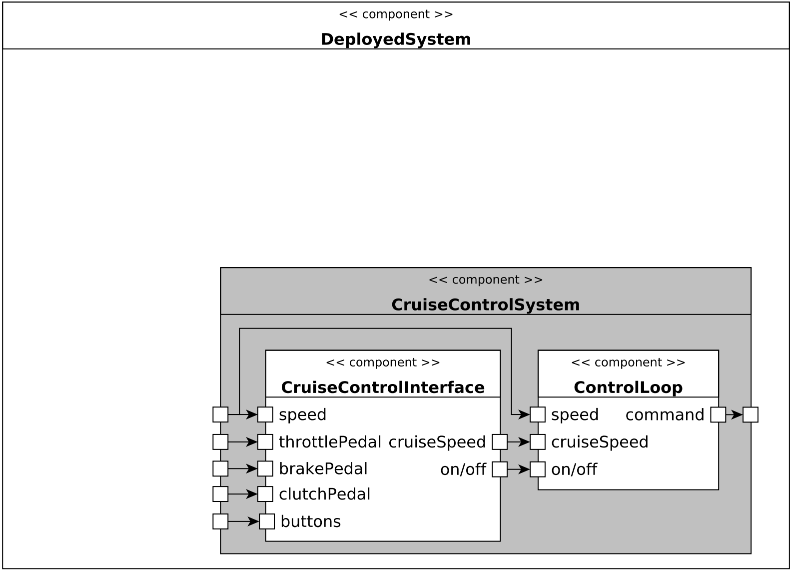
Cruise Control Overview



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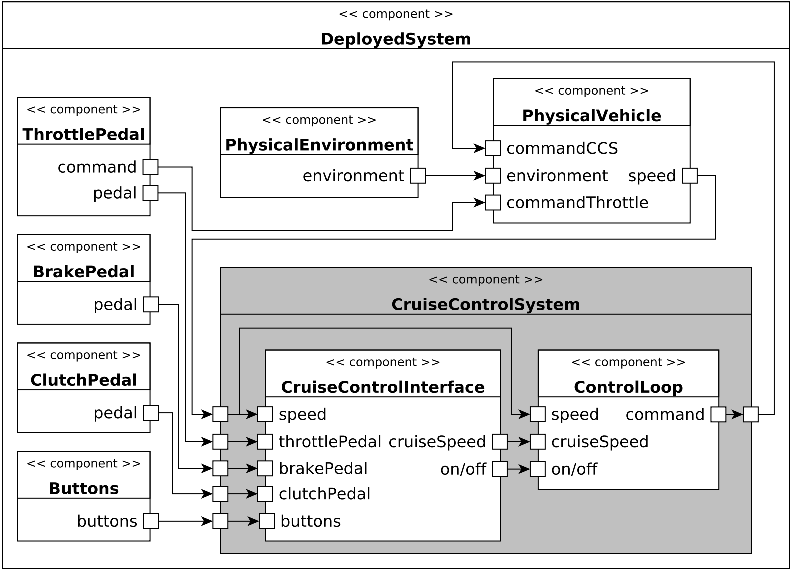

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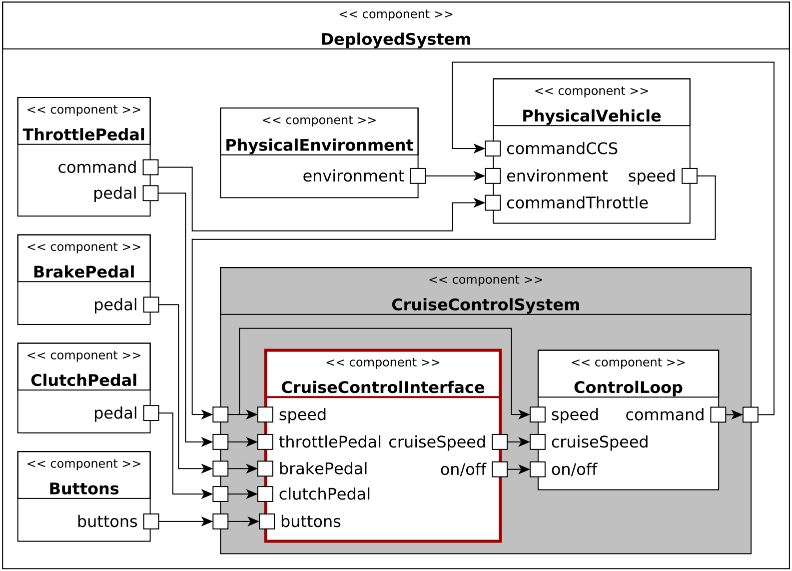

Cruise Control Interface Requirements

System requirements

1. After the detection of an event that turns the control loop off and until a contrary event is sent, the cruise control interface should not try to send new cruise speed setpoints.
2. The cruise speed setpoint should not be below 40 km/h or above 180 km/h.
3. When the system is engaged, the cruise speed setpoint should be defined.

Design model

Made using a UML subset that can be represented by:

- Class diagram
- Composite structure diagram
- State machines

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UML Observer Automata

Expressed directly in the design language

- UML class + UML state machine with *fail* states
- Extension of the expression language to read objects of the system and their properties

Requirements on observer automata

- Read-only access to system objects
- UML observer state machines must be:
  - **Deterministic** to avoid introducing non-determinism in the observed system execution
  - **Complete** to avoid blocking the system execution

Expressivity = safety properties (something bad happens)

- Analysis of finite execution traces for monitoring (current run)
- Verification problem reduced to a reachability problem (observer *fail* states)

UML Observer Automata

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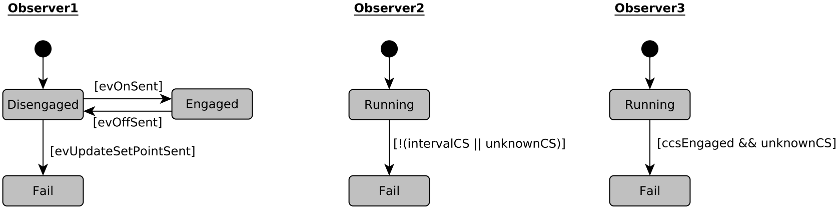

UML Observer Automata (Interpretation for Analysis Activities)

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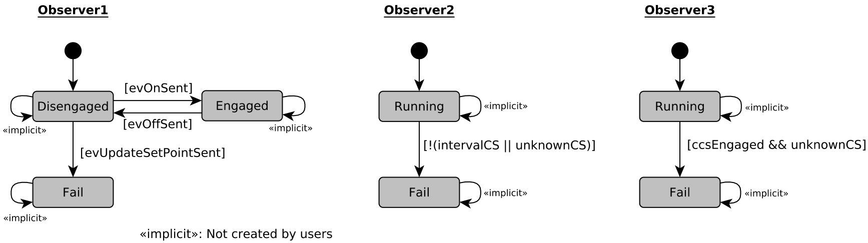

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Synchronous Composition

Principle

Each time a transition of the system model is fired, each observer automaton also makes a step to follow the system execution.

- At each step, a synchronous transition must be fired
- A synchronous transition is composed of:
  - One transition of the system
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- A synchronous transition is composed of:
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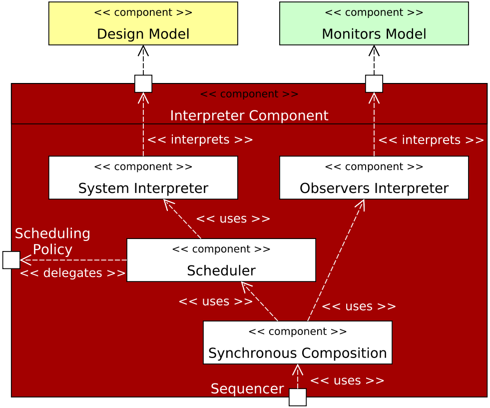
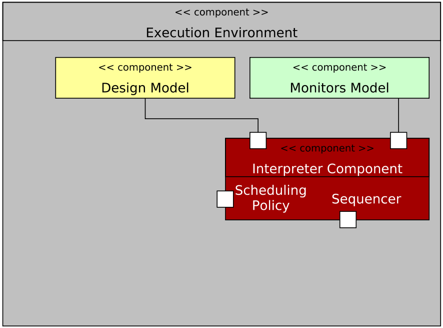
- **The UML semantics extension on which our approach relies**
- **Synchronous transitions are built on-the-fly for an efficient execution**

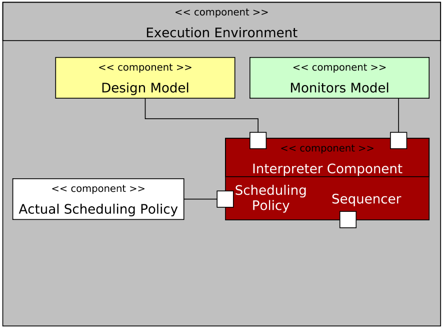


Runtime Monitoring with UML Observer Automata



Runtime Monitoring with UML Observer Automata

- Use the actual scheduling policy (e.g., round robin on active objects)



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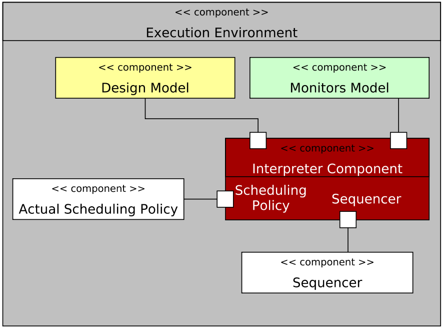
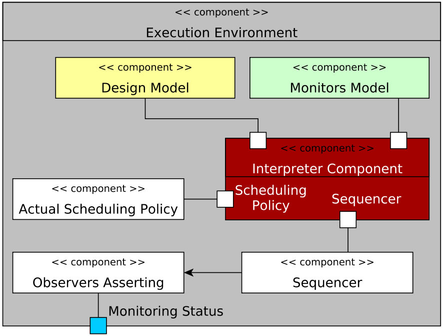
- Use the execution sequencer that fires synchronous transitions in loop



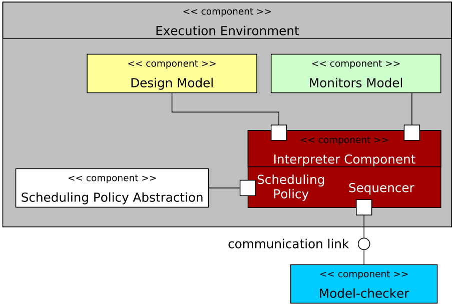
Runtime Monitoring with UML Observer Automata

- Use the actual scheduling policy (e.g., round robin on active objects)
- Use the execution sequencer that fires synchronous transitions in loop
- Check the current state of each observer at each step



Additional Usage: Model-checking with UML Observer Automata

- Use an abstraction of the scheduling policy to explore the whole model state-space
- The model-checker only has to use a reachability algorithm
  - `[] !|OBSERVER_FAIL(obs)|`



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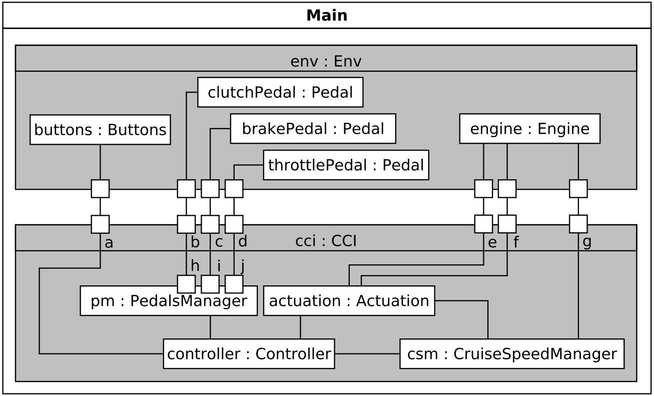
Cruise Control Interface Model Under Verification

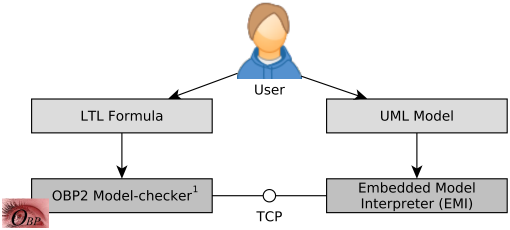
model under verification = system model + abstract environment model



Names of ports

a) cciButtonsPort
b) cciClutchPedalPort
c) cciBrakePedalPort
d) cciThrottlePedalPort
e) cciOnOffPort
f) cciSpeedPort
g) cciCruiseSpeedPort
h) pmClutchPedalPort
i) pmBrakePedalPort
j) pmThrottlePedalPort

Experiments



Experiments

- Compare verification results obtained with:
  - LTL formulae

[1] [Teodorov et al., 2017] `https://plug-obp.github.io/`

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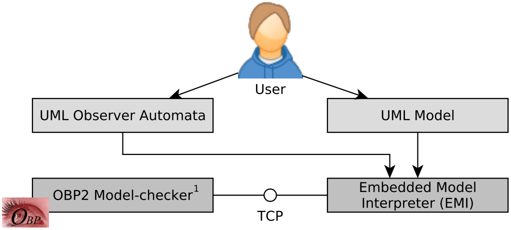

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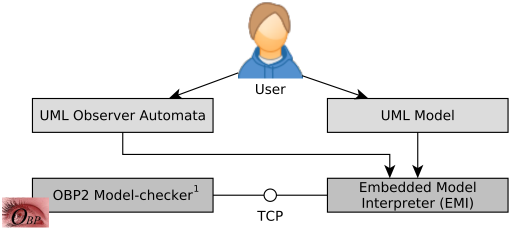


Experiments

- Compare verification results obtained with:
  - LTL formulae
  - UML observer automata
- Use to same UML observer automata to make runtime monitoring

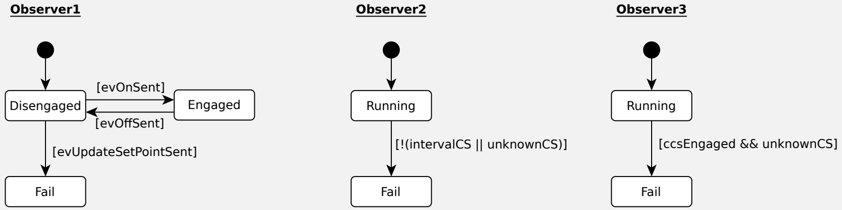
[1] [Teodorov et al., 2017] https://plug-obp.github.io/

Model-Checking of the Level Crossing Model

Expression of properties as LTL formulae

1. `[] ((|evOffSent| and !|evOnSent|) -> (!|evUpdateSetPointSent| W |evOnSent|))`
2. `[] (|intervalCS| or |unknownCS|)`
3. `[] (|ccsEngaged| -> !|unknownCS|)`

Expression of properties as UML observer automata



Results - Model-checking

	LTL Formulae	UML Observer Automata
Property 1	✓	✓
Property 2	✓	✓
Property 3	✗	✗

✓: Property verified ✗: Property violated

Analysis of the counter-example

Events *resetCS* and *disengage* could be processed in any order
$\Rightarrow$ Bad event interleaving

Model state-space

46,444,386 configurations linked by 82,734,350 transitions

Results - Monitoring

	Initial Model	Fixed Model
Property 1	● (green)	● (green)
Property 2	● (green)	● (green)
Property 3	● (red)	● (green)

● (green): No failure detected ● (red): Failure detected

Overhead of the monitoring infrastructure

- Execution performance: +6.5%
- Memory footprint: +1.2%

Results - Monitoring

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Property 2	● (green)	● (green)
Property 3	● (red)	● (green)

● (green): No failure detected   ● (red): Failure detected

Execution performance

- Estimation of the overhead:

$$overhead \approx 6.5 + \frac{1}{nb\_ao} \sum_{i=1}^{N} \frac{nb\_states_i}{nb\_outgoings_i}$$

- Relative cost of observer automata decreases as the size of the system model increases.

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- Embed these monitors with our model interpreter

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Proposed solution

- Express properties as UML observer automata directly in the design language
- Embed these monitors with our model interpreter

Results

1. No more semantic gap
2. Only one language to express system and monitors models

$\Rightarrow$ Helps engineers verify and monitor the embedded systems they are designing

Conclusion

Benefits

- The same UML observer automata can be used for model verification and runtime monitoring
- The use of formal verification techniques by engineers is facilitated

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Drawbacks

- Only observed failures can be detected
- Monitoring overhead (does not impede scalability)

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- The same UML observer automata can be used for model verification and runtime monitoring
- The use of formal verification techniques by engineers is facilitated

Drawbacks

- Only observed failures can be detected
- Monitoring overhead (does not impede scalability)

Perspectives

- Extend expressivity of guards in UML observer automata
- Integrate other model-based specification formalisms

Thank you for your attention

Bibliography

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