A Domain-Specific Language for Generic Interlocking Models and Their Properties

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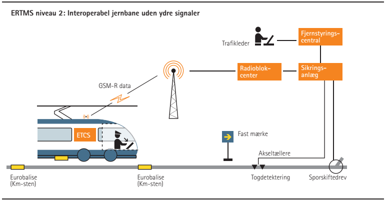
Outline

1. Introduction
   - Background on Interlocking Systems
   - Motivation

2. **IDL:** A Domain-Specific Language for Generic Interlocking Models

3. Conclusions

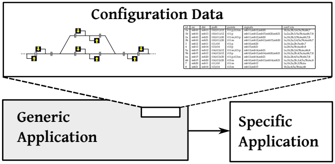
Interlocking Systems



Source: Banedanmark

- An *interlocking system* is a signalling system component responsible for *safe* routing of trains through a railway network.

State-of-the-art Architecture of Interlocking Systems

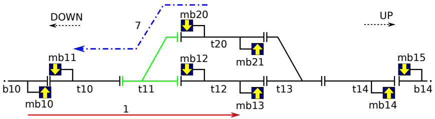


Product line paradigm:

- Interlocking systems come in *product lines*.
- Each product line has its own *generic application* which can be instantiated with *configuration data* to *specific applications* (product instances).
- *Configuration data* is specified by a *track plan* and an *interlocking table*.

Specification of Configuration Data – Example

(1) track plan:

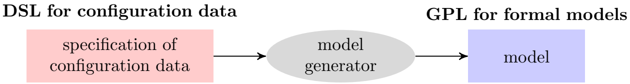


(2) interlocking table:

id	src	dst	path	points	signals	conflicts
1a	mb10	mb13	t10;t11;t12	t11:p;t13:m	mb11;mb12;mb20	1b;2a;2b;3;4;5a;5b;6b;7
1b	mb10	mb13	t10;t11;t12	t11:p	mb11;mb12;mb15;mb20;mb21	1a;2a;2b;3;5a;5b;6a;6b;7;8
2a	mb10	mb21	t10;t11;t20	t11:m;t13:p	mb11;mb12;mb20	1a;1b;2b;3;5b;6a;6b;7;8
2b	mb10	mb21	t10;t11;t20	t11:m	mb11;mb12;mb13;mb15;mb20	1a;1b;2a;3;4;5a;5b;6a;6b;7
3	mb12	mb11	t11;t10	t11:p	mb10;mb20	1a;1b;2a;2b;5a;6b;7
4	mb13	mb14	t13;t14	t13:p	mb15;mb21	1a;2b;5a;5b;6a;6b;8
5a	mb15	mb12	t14;t13;t12	t11:m;t13:p	mb13;mb14;mb21	1a;1b;2b;3;4;5b;6a;6b;8
5b	mb15	mb12	t14;t13;t12	t13:p	mb10;mb13;mb14;mb20;mb21	1a;1b;2a;2b;4;5a;6a;6b;7;8
6a	mb15	mb20	t14;t13;t20	t11:p;t13:m	mb13;mb14;mb21	1b;2a;2b;4;5a;5b;6b;7;8
6b	mb15	mb20	t14;t13;t20	t13:m	mb10;mb12;mb13;mb14;mb21	1a;1b;2a;2b;3;4;5a;5b;6a;8
7	mb20	mb11	t11;t10	t11:m	mb10;mb12	1a;1b;2a;2b;3;5b;6a
8	mb21	mb14	t13;t14	t13:m	mb13;mb15	1b;2a;4;5a;5b;6a;6b

Modelling Interlocking Systems for Verification

- State-of-the-art FMs for interlocking verification provide a *model-generator*:



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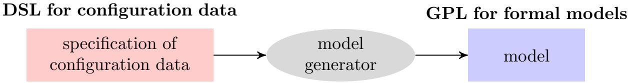

- Inconveniences:
  - A new model generator is needed: (1) for each new product line, (2) when making different model abstractions for the same product line, and (3) when fixing modelling bugs.

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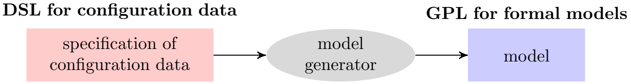
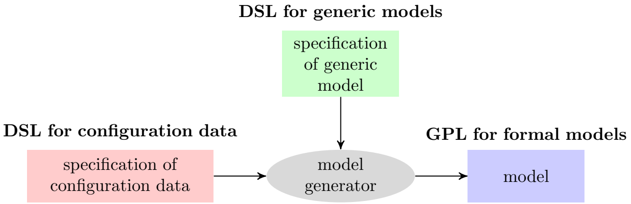


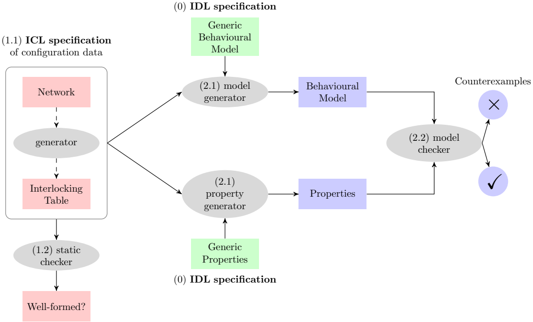
- Inconveniences:
  - A new model generator is needed: (1) for each new product line, (2) when making different model abstractions for the same product line, and (3) when fixing modelling bugs.
- We suggest to let the generator take a 2. argument in **a DSL for generic models**:



Advantages of the extra DSL: (1) Easier to read, write and change generic models. (2) Need only model generator.

RobustRailS Verification Method & Tools

- In the **RobustRailS** project (2012-17) supporting the Danish re-signalling programme, we have a model generator with inputs from *two DSLs*: **IDL** and **ICL**.



For each product line:

- Generic model and properties are defined once-and-for-all in **IDL**.
- Two-step verification for each product instance, (1) configuration data is defined in **ICL** and verified by a static analyser, and (2) models and properties generated and verified by SMT-based model checking (using induction).

For more details on the method and its applications: *Vu, Haxthausen & Peleska: Formal modelling and verification of interlocking systems featuring sequential release.* Science of Comp. Progr., *133, Part 2:91 – 115, 2017.*

Outline

IDL Specifications – Overview

- major specification elements:
  - *generic variable declarations* (encodings)
  - *generic transition relation* definition
  - *generic properties* (state invariants)
  - *macros*

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  - pre-defined *element types* (e.g. **Point**) each representing a set of elements (e.g. points) in the configuration data
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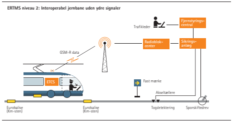
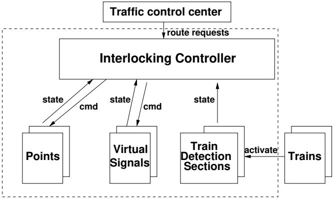
  - built-in *domain-specific functions* for generic references to elements in the configuration data(e.g. **first**(r))
- semantics: $\mathcal{M} : Specification \rightarrow (ConfigData \rightarrow Model \times Properties)$
  $\mathcal{M}(spec)(cd) = (M, P)$, where
  - $M = (S, I, R)$ is a behavioural model with
    - state space S: a set of variable assignments $\sigma : V \rightarrow Value$ for a set V of variables.
    - initial condition I: a predicate over variables in V
    - transition relation R: a predicate over variable in V (pre states) and V' (post states).
  - P is a predicate over variables in V representing desired state invariants.

Interlocking System Case Study





Traditional control loop:

- The interlocking receives *route requests* from the traffic control center.
- It sets a requested route, if no conflicting route is already set.
- While setting a route it commands points and signals to the settings required for the route (specified in the interlocking table).
- Once a route is set, it commands the entry signal to OPEN.
- Once a train enters the route, it sets the (virtual) signal to CLOSED.
- It releases the route, when the train has finished using it.

Generic Variable Declarations – Example

```
encoding /* generic variable declarations */
  Linear ::
    CNT  → [INPUT,"unsigned int",0,0,2]    /* occupied counter */
  Point ::
    CNT  → [INPUT,"unsigned int",0,0,2]    /* occupied counter */
    POS  → [INPUT,"unsigned int",0,0,1]    /* actual position */
    CMD  → [OUTPUT,"unsigned int",0,0,1]   /* commanded position */
  Signal ::
    ACT  → [INPUT,"unsigned int",0,0,1]    /* actual aspect */
    CMD  → [OUTPUT,"unsigned int",0,0,1]   /* commanded aspect */
  Route ::
    MODE → [LOCAL,"unsigned int",0,0,4]    /* current mode */
```

Instantiation of Generic Variable Declarations

encoding /∗ *generic variable declarations* ∗/

  Linear ::

    CNT → [**INPUT**,"unsigned int",0,0,2] /∗ *occupied counter* ∗/

  Point ::

    CNT → [**INPUT**,"unsigned int",0,0,2] /∗ *occupied counter* ∗/

    POS → [**INPUT**,"unsigned int",0,0,1] /∗ *actual position* ∗/

    CMD → [**OUTPUT**,"unsigned int",0,0,1] /∗ *commanded position* ∗/

  Signal ::

    ACT → [**INPUT**,"unsigned int",0,0,1] /∗ *actual aspect* ∗/

    CMD → [**OUTPUT**,"unsigned int",0,0,1] /∗ *commanded aspect* ∗/

  Route ::

    MODE → [**LOCAL**,"unsigned int",0,0,4] /∗ *current mode* ∗/

gives

- state space $S \equiv S_{\textsf{Linear}} \times \cdots \times S_{\textsf{Route}}$
- initial condition $I \equiv I_{\textsf{Linear}} \wedge \cdots \wedge I_{\textsf{Route}}$

Instantiation of Generic Variable Declarations

Instantiation of

encoding /∗ *generic variable declarations* ∗/
  Linear ::
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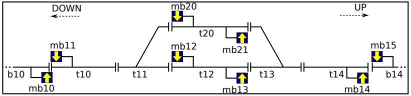
with



Linear = { t10, t12, t14, t20 }

gives rise to the following concrete variables:

t10.CNT, t12.CNT, t14.CNT, t20.CNT

all with domain $0..2$ and initial value 0.

$S_{\textsf{Linear}} \equiv \{\texttt{t10.CNT}, \texttt{t12.CNT}, \texttt{t14.CNT}, \texttt{t20.CNT}\} \to \{0..2\}$

$I_{\textsf{Linear}} \equiv \texttt{t10.CNT} = 0 \wedge \texttt{t12.CNT} = 0 \wedge \texttt{t14.CNT} = 0 \wedge \texttt{t20.CNT} = 0$

Macros - Examples

macro /* *signal aspects* */

def CLOSED = 0, **def** OPEN = 1

macro /* *route modes* */

def FREE = 0, ..., **def** LOCKED = 3, **def** OCCUPIED = 4

Generic Transition Relation Definition

General form:

transrel `te`

where `te` is a *(generic) transition relation expression* in one of the forms:

- *atomic transition rule*: $\texttt{guard-expr} \longrightarrow \texttt{update-expr}$
- *non-deterministic choice*: $\texttt{te}_1\ [=]\ \texttt{te}_2$
- *prioritised choice*: $\texttt{te}_1\ [>]\ \texttt{te}_2$
- *quantified transition rule*: $[=]\ \texttt{id : ElementType} \bullet \texttt{te}$

For the running example, the transition rule takes the form

transrel

$$\texttt{te}_{\texttt{route\_dispatcher}}\ [=]\ (\texttt{te}_{\texttt{IXL}}\ [>]\ (\texttt{te}_{\texttt{points}}\ [=]\ \texttt{te}_{\texttt{signals}})\ [>]\ \texttt{te}_{\texttt{sections}})$$

- where $te_{route\_dispatcher}$, te_{IXL}, te_{points}, $te_{signals}$, and $te_{sections}$ consist of quantified transition rules describing the behaviour of the route dispatcher, the route controller, and the track elements.

Instantiation of Transition Relation

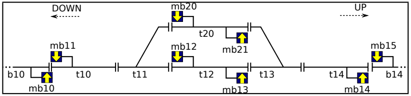
- Instantiation of **transrel** `te` with configuration data yields a transition relation R in predicate form. R is found from `te` in three steps:

  0. Macros are expanded away.
  1. Instantiation step: generic constructs are expanded away
     - Quantified transition rules $[=]$ `id : ElementType • te` are expanded to non-deterministic choices.
     - Applications of domain-specific functions are expanded.
  2. Semantic transformation step: remaining constructs ($\longrightarrow$, $[=]$, and $[>]$) are expanded away.

Example: Quantified Transition Rule for Points

$$([=]\ p : \textbf{Point} \bullet\ [\text{switch\_point}]\ \ p.\text{CMD} \neq p.\text{POS} \longrightarrow p.\text{POS}' = p.\text{CMD})$$

Instantiation with



Point = { t11, t13 }

first expands to

$$(\text{t11.CMD} \neq \text{t11.POS} \longrightarrow \text{t11.POS}' = \text{t11.CMD})\ [=]$$
$$(\text{t13.CMD} \neq \text{t13.POS} \longrightarrow \text{t13.POS}' = \text{t13.CMD})$$

and then gives

$$(\text{t11.CMD} \neq \text{t11.POS} \wedge \text{t11.POS}' = \text{t11.CMD} \wedge \phi_{t11.POS}) \vee$$
$$(\text{t13.CMD} \neq \text{t13.POS} \wedge \text{t13.POS}' = \text{t13.CMD} \wedge \phi_{t13.POS})$$

where $\phi_{id.v} \equiv \wedge_{x \in V \setminus \{id.v\}}(x' = x)$ is a formula expressing that all variable instances except $id.v$ remain unchanged by the transition.

Example: a Transition Rule for the Interlocking

$$([=]\ r : \textbf{Route} \bullet [\,\text{train\_enters\_route}\,]$$
$$r.\text{MODE} = \text{LOCKED} \wedge \textbf{first}(r).\text{CNT} > 0$$
$$\longrightarrow$$
$$r.\text{MODE}' = \text{OCCUPIED} \wedge \textbf{src}(r).\text{CMD}' = \text{CLOSED}$$
$$)$$

Instantiation with

id	src	dst	path	points	signals	conflicts
1a	mb10	mb13	t10;t11;t12	t11:p;t13:m	mb11;mb12;mb20	1b;2a;2b;3;4;5a;5b;6b;7
...	...	...	...	...	...	...
8	mb21	mb14	t13;t14	t13:m	mb13;mb15	1b;2a;4;5a;5b;6a;6b

(for which **Route** = { r1a, ..., r8 }) yields the relation:

$R_{r1a} \vee \ldots \vee R_{r8}$, where e.g.

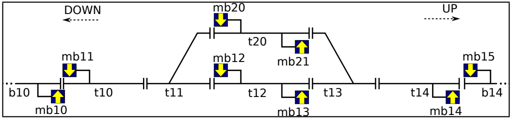
$$R_{r1a} \equiv$$
$$(\texttt{r1a.MODE} = 3 \wedge \texttt{t10.CNT} > 0) \wedge (\texttt{r1a.MODE}' = 4 \wedge \texttt{mb10.CMD}' = 0)$$
$$\wedge\ (\wedge_{\texttt{x} \in \texttt{V} \setminus \{\texttt{r1a.MODE},\texttt{mb10.CMD}\}} (\texttt{x}' = \texttt{x}))$$

Generic Properties – Example

invariant

[no_collision] $(\forall s : \textbf{Section} \bullet s.\mathrm{CNT} < 2)$

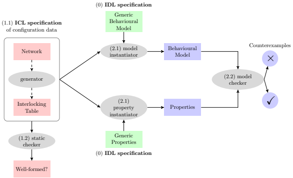
Instantiation with



yields the concrete property:

$$P \equiv \texttt{t10}.\mathrm{CNT} < 2 \land \cdots \land \texttt{t14}.\mathrm{CNT} < 2$$

Conclusions



Contributions:

- Suggestion to use a *domain-specific language* for *generic* interlocking models and their properties.
- *Advantages:* easier to read, write and change generic models and properties.
- Presented such a language.
- The language has been given a *semantics* defining the result of instantiating a generic specification with configuration data.
- The language and generator tools based on the semantics have been *implemented* as part of the **RobustRailS** tool set using Verified's **RT-Tester** tool set as backend.
- These have successfully been *applied* (1) to specify generic models of the novel Danish ERTMS 2 based interlocking systems and (2) to instantiate these for real-world lines and stations. See Vu, Haxthausen & Peleska: Formal modelling and verification of interlocking systems featuring sequential release. *Science of Computer Programming*, 133, Part 2:91 – 115, 2017.

Future work:

- Investigate to which extend the language could be applied to other classes of interlocking systems.
- Make extensions/adaptions of the language.

Questions?