Formally Verified Animation for RoboChart Using Interaction Trees

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Outline

Background and motivations

RoboChart model

Animation of RoboChart

Operational Semantics for RoboChart

Conclusion

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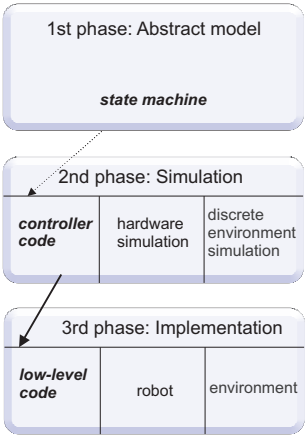
Current practice and problems



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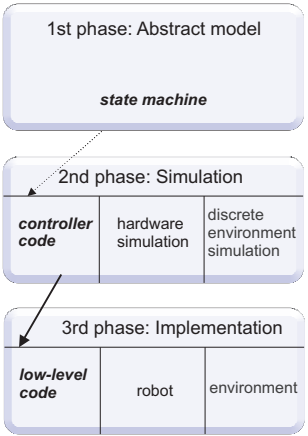

- No models, or models without precise syntax or formal semantics,
- Time and uncertainty: discussed informally,
- No tool support,
- Loose connections of artefacts,
- Trial-and-error,
- No assurance.

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RoboStar

- RoboStar framework: modern modelling and verification technologies, software engineering of robotics

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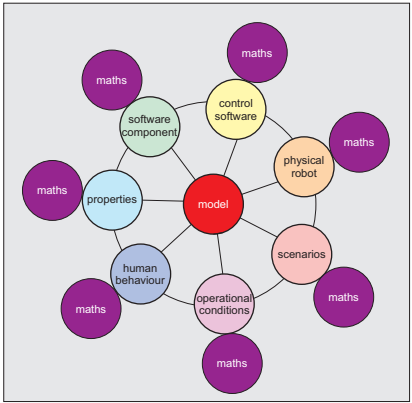
- Vision: model centred, mathematical semantics



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RoboChart

- Core notation of RoboStar, DSL for robotics, state machines + time + probability

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- A component model (platform independent + parallel composition of state machines)
- Denotational semantics (CSP and MDP) and verification (FDR and PRISM)
- Animated available in FDR (ProBE animator), or in PRISM (simulator)
- but the animation is low-level and not very helpful (for our purpose)

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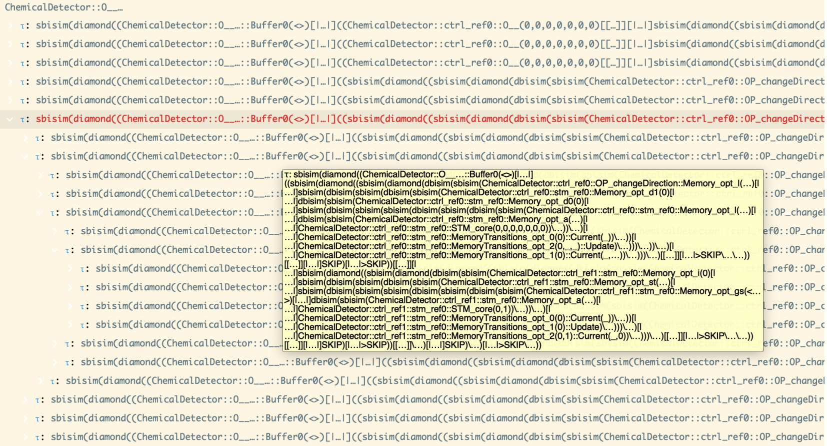
Animation using FDR



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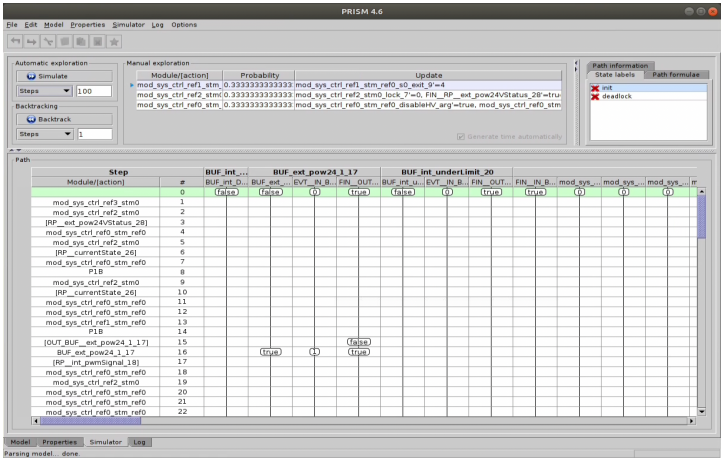
Animation using PRISM



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Why Animation?

(Kazmierczak et al. 1998)

- Easily automated and cheap to perform (vs. formal verification),

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- Interactive testing of models and properties,
- Shorten learning curve of RoboChart (semantics): students, roboticists, formal experts.

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Recent work

Foster, S., Hur, C.K., Woodcock, J.: Formally verified simulations of state-rich processes using interaction trees in Isabelle/HOL. CONCUR (2021)

- Interaction trees (ITrees) in Isabelle/HOL, with ITrees-based semantics for CSP,
- Formally verified animation for CSP (code generator in Isabelle/HOL),
- Implemented most CSP processes and operators.

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Contributions

- Operational semantics for RoboChart: ITrees-based CSP,
- Mechanisation of the semantics of the autonomous chemical detector model in Isabelle,
- Animation of the model,
- Implementation of three extra CSP operators (interrupt, exception, and renaming),
- Implementation of a bounded sequence type for code generation.

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Benefits

- Unification of verification and animation,
- Support richer RoboChart types and expressions, and functions,
- Characterise systems with an infinite number of states symbolically,
- Functional algorithms and data refinement: automated,
- Could be fully automated: from RoboChart models to final Haskell code.

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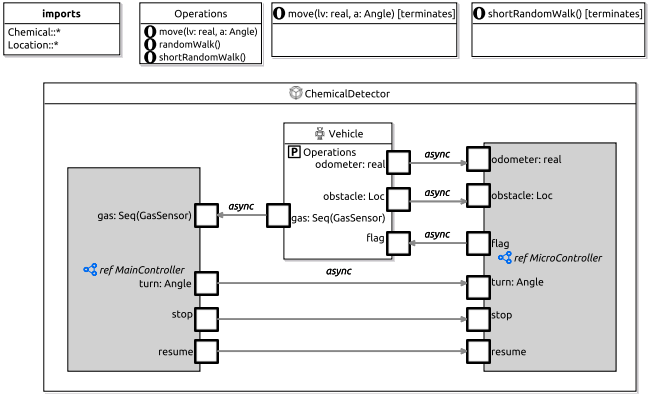
Autonomous chemical detector - module

From the papers (Hilder et al. 2012) and (Miyazawa et al., 2019).



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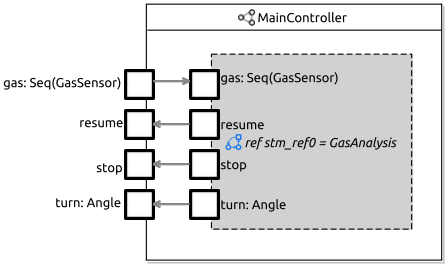
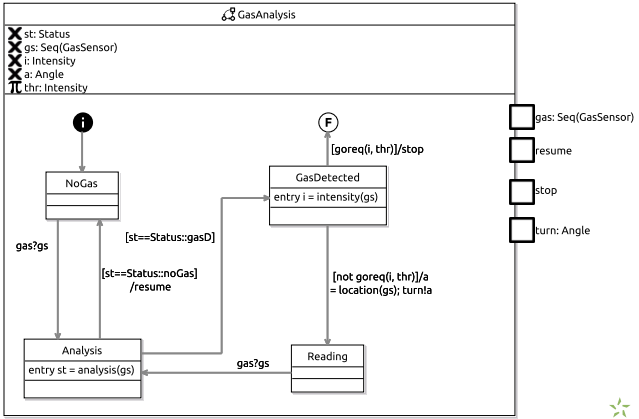
Autonomous chemical detector - main controller





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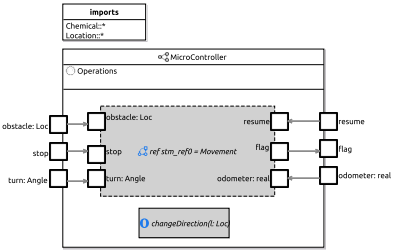
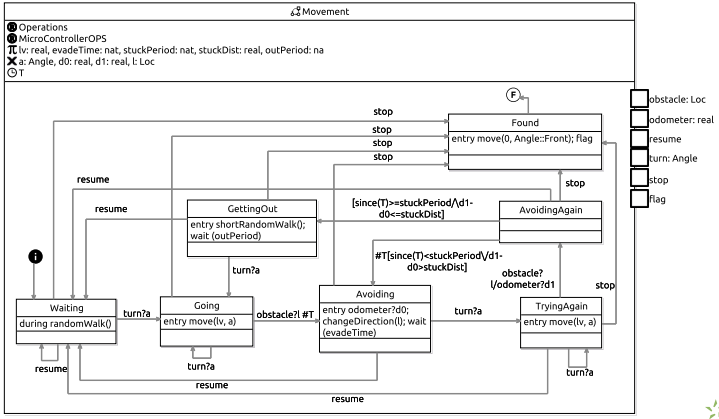
Autonomous chemical detector - micro controller





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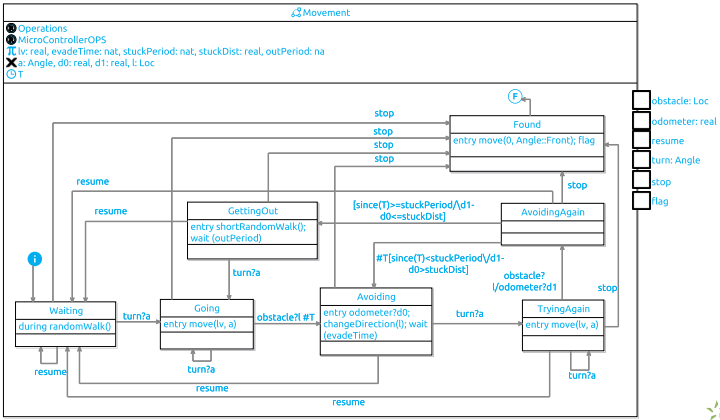
Animation of RoboChart (video)

- Model
- Controllers
- State machines

Code generation in Isabelle, animation (Isabelle console or OS console)



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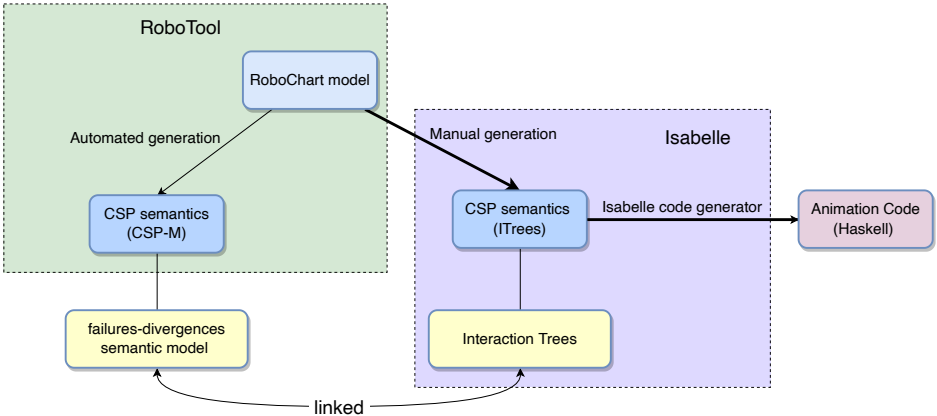
Animation of RoboChart - our approach



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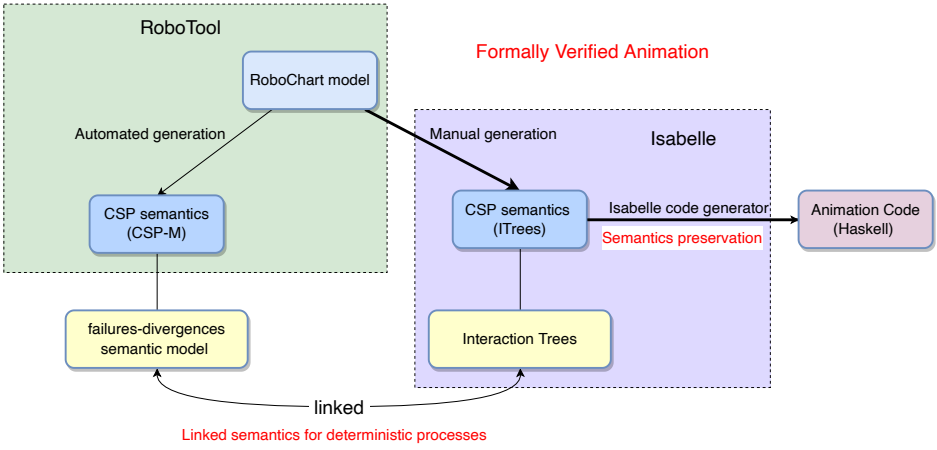
Animation of RoboChart - our approach (semantics)



Interaction Trees (Xia et al. 2019) in Isabelle/HOL

Coinductive trees, with potentially infinite breadth and depth, used to represent the ways a process communicates with its environment and evolves over time.

Definition (Interaction trees)

```
codatatype ('e, 'r) itree =
  Ret 'r | - ‹ Terminate, returning a value ›
  Sil "('e, 'r) itree" | - ‹ Invisible event ›
  Vis "'e ↛ ('e, 'r) itree" - ‹ Visible events and continuations ›
```

Notation: $\checkmark_v$ for `Ret` v, τP for `Sil` P, $[\!]\ e \in E \to P(e)$ for `Vis` $(\lambda\, e \in E \bullet P(e))$.

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Existing CSP Processes and Operators

- *skip*, *stop*, *div*, *run*
- Input event: *inp_in* $c\ A$
- Output event: *outp* $c\ v$
- Sequential composition (monad): $P \gg\!= K$
  - *do* $\{x \leftarrow$ *inp_in* $c\ A;$ *outp* $d\ (2 \cdot x);$ *Ret* $x\}$
- External choice: $P \Box Q$
- Parallel composition: $P \parallel_A Q$ (interleave $|||$).
- Hiding: $P \setminus A$

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Extra CSP operators - Interrupt

Definition (Interrupt)

$P \triangle Q$ behaves like P except that if at any time Q performs one of its initial events then it takes over, defined corecursively.

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$$(\mathit{Sil}\, P') \triangle Q = \mathit{Sil}\, (P' \triangle Q) \qquad P \triangle (\mathit{Sil}\, Q') = \mathit{Sil}\, (P \triangle Q')$$

$$(\mathit{Ret}\, x) \triangle Q = \mathit{Ret}\, x \qquad P \triangle (\mathit{Ret}\, x) = \mathit{Ret}\, x$$

$$(\mathit{Vis}\, F) \triangle (\mathit{Vis}\, G) = \mathit{Vis}\, \big(\{e \mapsto (P' \triangle Q) \mid (e \mapsto P') \in (\mathsf{dom}(G) \lhd F)\} \oplus G \big)$$

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Example

- $(\mathit{Ret}\, x) \triangle Q = \mathit{Ret}\, x$, and $(a \to P) \triangle (\mathit{Ret}\, x) = \mathit{Ret}\, x$
- Priority to Q: $(a \to P) \triangle (a \to Q) = a \to Q$

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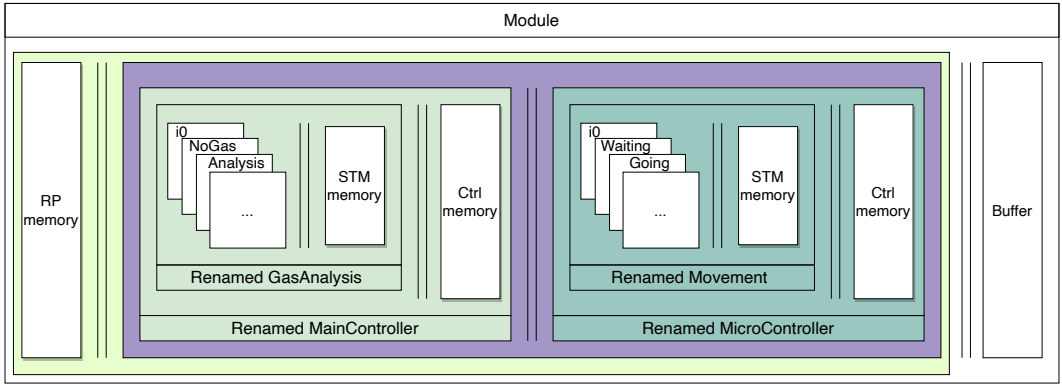
RoboChart semantics



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RoboChart data types

RoboChart types	Isabelle types	Note
basic primitive types: nat, int, ...	`natural`, `integer`, ...	target language types
abstract primitive type	`PrimType`	Chem, Intensity
enumerations	**`datatype`**	
records	**`record`**	
mathematical types: sets, relations, ...	Z mathematical toolkit	Bounded finite sequences

Definition (Abstract primitive type to finite enumerations)

```
datatype ('t, 'a::finite) PrimType = PrimTypeC 'a
```

Definition (Bounded finite sequence)

```
typedef ('a,'n::finite) blist = {xs::'a list. length xs≤CARD('n)}
```

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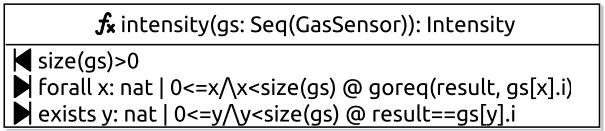
RoboChart functions



Definition (intensity function)

```
definition "pre_Chemical_intensity gs = (blength gs > 0)"
definition "Chemical_intensity gs = (THE result.
  (∀x::nat<blength gs. Chemical_goreq(result, gs_i (bnth gs x)))∧
  (∃x::nat<blength gs. result = gs_i (bnth gs x)))"
```

Detected an error in the original model where x <= size(gs) is used.

Channel type

A process is of type (E, V)*itree*;
Two processes in parallel composition have the same type: E and V.

```
chantype Chan_Movement =
  internal_Movement  :: TIDS_Movement
  terminate_Movement :: unit
  enter_Movement     :: "SIDS_Movement×SIDS_Movement" ...
  get_l_Movement     :: "Location_Loc"
  set_l_Movement     :: "Location_Loc"
  set_EXT_l_Movement :: "Location_Loc"
  obstacle__Movement :: "TIDS_Movement×InOut×Location_Loc"
  obstacle_Movement  :: "InOut×Location_Loc" ...
  moveCall_Movement  :: "core_real×Chemical_Angle" ...
```

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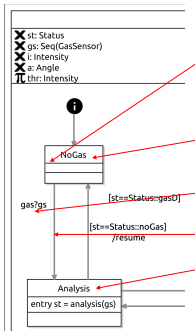
RoboChart States




```
definition State_GasAnalysis_NoGas where
"State_GasAnalysis_NoGas =
  loop (λ (id::integer).
    do {sd ← inp_in enter_GasAnalysis_Other_SIDs_to_NoGas_GasAnalysis ;
        — ‹ State passed to next loop, including a condition initially True. ›
        ret ← Ret (True, id, fst sd) ;
        — ‹ @{verbatim State_GasAnalysis_NoGas_execute} ›
        (iterate
           — ‹ condition ›
           (λ s. fst s)
           — ‹ P ›
           (λ s.
            do {
            outp_entered_GasAnalysis (snd (snd s), SID_GasAnalysis_NoGas);
            (do {skip ; stop} △
              (
              — ‹ @{verbatim T_GasAnalysis_t2} ›
              do {t ← inp_in gas__GasAnalysis (set [(TID_GasAnalysis_t2, din, gs)
                                 gs ← (lseq gassensor_enum)]) ;
                  outp_set_gs_GasAnalysis (snd (snd t)) ;
                  outp_exit_GasAnalysis (SID_GasAnalysis_NoGas, SID_GasAnalysis_NoGas);
                  outp_exited_GasAnalysis (SID_GasAnalysis_NoGas, SID_GasAnalysis_NoGas);
                  outp_enter_GasAnalysis (SID_GasAnalysis_NoGas, SID_GasAnalysis_Analysis);
                  outp_entered_GasAnalysis (SID_GasAnalysis_NoGas, SID_GasAnalysis_Analysis);
                  Ret(False, fst (snd s), SID_GasAnalysis_NoGas)
                 } □
              (exit_events_GasAnalysis (fst (snd s)) SID_GasAnalysis_NoGas
                tids_GasAnalysis_NoGas Other_SIDs_to_NoGas_GasAnalysis)
              )
            )
           })
           — ‹ The previous state: a triple ›
           (ret)
        ) ;
        Ret (id)
    }
  )
"
```

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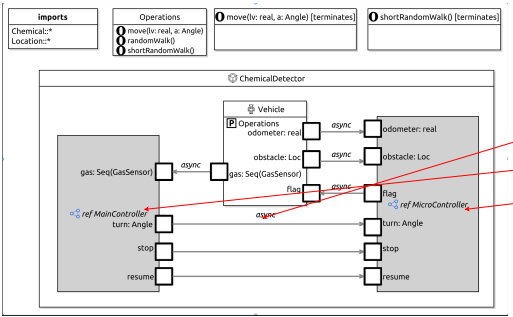
RoboChart Module




```
definition D__ChemicalDetector where
"D__ChemicalDetector (idd::integer) =
  (
    (
      (par_hide
        (discard_state (buffer0 []))
        ChemicalDetector_controllers_buffer_events
        (
          (
            (
              (rename_D__MainController idd)
              ||ₛ (ChemicalDetector_controllers_sync_events) ↙
              (rename_D__MicroController idd)
            ) \ (ChemicalDetector_controllers_sync_events - (set [terminate_C ()]))
          )
          ||ₛ (set []) ↙
          Memory_ChemicalDetector
        )
      ) ⟦ set [terminate_C ()] ▷ skip
    ) \ (set [terminate_C ()])
  )
"
```

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- Applications: sound runtime monitors, concrete implementation of RoboChart controllers (for verified ROS nodes).

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References

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- Xia et al. Interaction trees: representing recursive and impure programs in Coq. POPL (2019)
- Foster et al. Formally verified simulations of state-rich processes using interaction trees in Isabelle/HOL. CONCUR (2021)

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