Contract-based Compositional Verification of Infinite-State Reactive Systems

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VSTTE 2018 — July 18-19, 2018, Oxford, UK

Acknowledgments

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(*) Senior Kind 2 developer

Embedded Software

- Used to control the behavior of physical devices
- Typically *reactive*: continually map inputs and internal state to outputs
- Often mission- or safety-critical
- Developed modularly from components
- Development model-based

Model-based Software Development

- Software components modeled formally as computational systems
- Synchronous/asynchronous computational model
- Formal system and components amenable to formal analysis
- Expected behavior specified in terms of safety/liveness properties
- Great progress in last two decades in automating verification
- Compositional reasoning crucial for scalability

This Talk

Experiences in

- designing a contract language on top of a synchronous, dataflow modeling language for embedded software
- leveraging contracts for
  - modular and incremental development
  - compositional model checking

Discussion of

- implementation in the Kind 2 model checker
- a case study with a realistic system

Compositional Reasoning: Assume-Guarantee Paradigm

Setting [McMillan, 1999, Bobaru et al., 2008]:

- (Reactive) system is composed of several components
- Every component $C[\mathbf{x}, \mathbf{y}]$ with inputs $\mathbf{x}$ and outputs $\mathbf{y}$ has a *contract*:
  - a set $\mathcal{A}[\mathbf{x}, \mathbf{y}]$ of *assumptions* on C's current input and past I/O behavior
  - a set $\mathcal{G}[\mathbf{x}, \mathbf{y}]$ of *guarantees* on expected behavior, provided assumptions $\mathcal{A}[\mathbf{x}, \mathbf{y}]$ hold

Assume-Guarantee Reasoning (simplified form)

Def. C *respects* its contract $\langle \mathcal{A},\ \mathcal{G} \rangle$ if all of its executions satisfy

$$\Box \mathcal{A} \Rightarrow \Box \mathcal{G}$$

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Def. $C_1[\mathbf{x}_1, \mathbf{y}_1]$ *uses* $C_2[\mathbf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input $\mathbf{i}$ and reads the corresponding output in $\mathbf{o}$

C_1 uses C_2 *safely* if C_1's executions satisfy $\Box \mathcal{A}_2[\mathbf{i}, \mathbf{o}]$

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Obs. If

1. C_1 uses C_2 safely and
2. C_2 respects its own contract $\langle \mathcal{A}_2,\ \mathcal{G}_2 \rangle$

then C_2 can be abstracted by $\mathcal{A}_2[\mathbf{i}, \mathbf{o}] \wedge \mathcal{G}_2[\mathbf{i}, \mathbf{o}]$ in C_1

Modeling Reactive System Components in Lustre

Lustre: a synchronous dataflow language [Halbwachs et al., 1992]

Synchronous:

all components run in parallel, based on a universal clock

Dataflow:

inputs, outputs, variables, constants are all infinite streams of values

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Declarative:

components defined by set of equations, no statements

A Simple Lustre Component

```
node average (x, y: real) returns (out: real);
let
  out = (x + y) / 2.0 ;
tel
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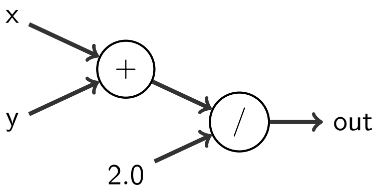
Circuit view:



A simple example

```
node average (x, y: real) returns (out: real);
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```

Mathematical view:

$$\forall i \in \mathbb{N},\ \mathsf{out}_i = \frac{\mathsf{x}_i + \mathsf{y}_i}{2}$$

A simple example

```
node average (x, y: real) returns (out: real);
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tel
```

Transition system unrolled view:

clock ticks   0   1   2   3   ⋯

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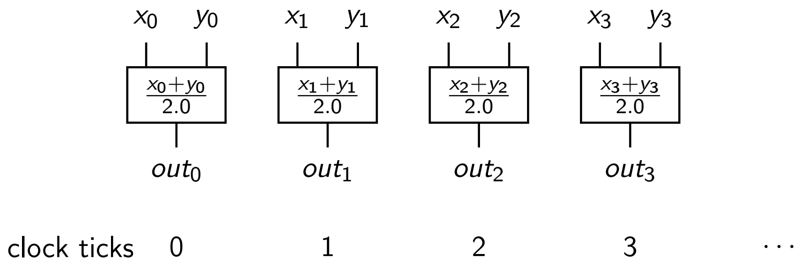
Transition system unrolled view:



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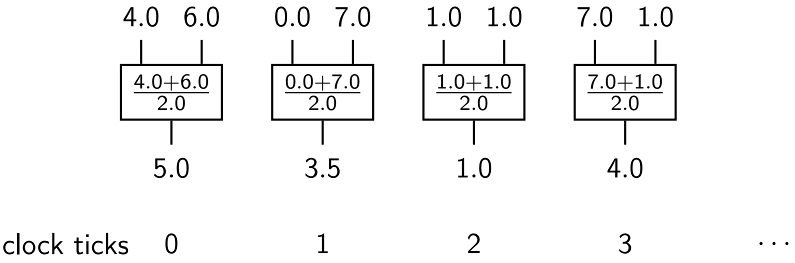

Combinational programs

- Basic types: `bool` , `int` , `real`

- Constants (i.e., constant streams):

`2`	2	2	2	2	2	...
`true`	`true`	`true`	`true`	`true`	`true`	...

- Pointwise operators:

x	x_0	x_1	x_2	x_3	x_4	...
y	y_0	y_1	y_2	y_3	y_4	...
$x + y$	$x_0 + y_0$	$x_1 + y_1$	$x_2 + y_2$	$x_3 + y_3$	$x_4 + y_4$	...

- All customary operators are provided

Combinational Components

Conditional expressions

Local variables

```
node max (a,b: real) returns (out: real);
var
  c: bool;
let
  out = if c then a else b;
  c = a >= b;
tel
```

Combinational Components

Conditional expressions

Local variables

```
node max (a,b: real) returns (out: real);
var
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let
  out = if c then a else b;
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tel
```

- Equation order does not matter
- Set of equations, not sequence of statements
- Causality is resolved syntactically

Stateful Components

Previous operator `pre` :

$(\texttt{pre}\ x)_0$	undefined
$(\texttt{pre}\ x)_i = x_{i-1}$	for $i > 0$

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Initialization `->` :

$(x\ \texttt{->}\ y)_0 = x_0$

$(x\ \texttt{->}\ y)_i = y_i$ for $i > 0$

Examples:

x	x_0	x_1	x_2	x_3	x_4	x_5	...
`pre` x	//	x_0	x_1	x_2	x_3	x_4	...
y	y_0	y_1	y_2	y_3	y_4	y_5	...
x `->` y	x_0	y_1	y_2	y_3	y_4	y_5	...
2	2	2	2	2	2	2	...
2 `->` (`pre` x)	2	x_0	x_1	x_2	x_3	x_4	...

Modularity

Components defined as *nodes* parametrized by inputs

Can have several outputs

Can be understood as macros

```
node MinMaxSoFar ( X : real ) returns ( Min, Max : real );
let
  Min = X -> if (X < pre Min) then X else pre Min ;
  Max = X -> if (X > pre Max) then X else pre Max ;
tel

node MinMaxAverageSoFar ( X: real ) returns ( Y: real ) ;
var Min, Max: real ;
let
  Min, Max = MinMax(X) ;
  Y = (Min + Max)/2.0 ;
tel
```

CocoSpec Contract Language

Our extension of Lustre with contracts [Champion et al., 2016a]

Objectives:

- follow assume-guarantee paradigm
- ease process of writing and reading formal specifications
- facilitate automatic verification of specs
- improve feedback to user after analysis
- partition information for specification-driven test generation

Contract-based specification

Contracts over components

- describe their behavior under some assumptions
- correspond to requirements from specification documents

Contract Example

stopwatch(`toggle`, `reset`) $\rightarrow$ `count`

Assumptions:

reasonable input	$\neg$(`reset` $\wedge$ `toggle`)

Guarantees:

output range	`count` ≥ 0,	initially	0
resetting	`reset`	implies	`count` is 0
running	$\neg$`reset` $\wedge$ `on`	implies	`count` increases by 1
stopped	$\neg$`reset` $\wedge$ $\neg$`on`	implies	`count` does not change

Contract Example

```
node stopwatch(toggle, reset: bool) returns (c: int);
(*@contract
  var on: bool = toggle ->
    (pre on and not toggle) or (not pre on and toggle) ;

  assume not (reset and toggle) ;
  guarantee c = 0 -> c >= 0 ;

  guarantee reset => c = 0 ;
  guarantee (not reset and on) => c = (1 -> pre c + 1) ;
  guarantee (not reset and not on) => c = (0 -> pre c) ;
*)
let ... tel
```

Contracts as an Abstraction Mechanism

A component's contract is usually simpler than the component's definition

A contract is a declarative over-approximation of the component

Contracts enable modular and compositional analyses in alternative to a monolithic one

In compositional analyses we abstract away the complexity of a subsystem by its contract

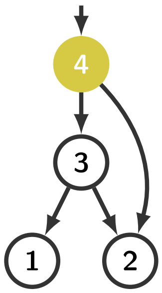
Monolithic Analysis

Monolithic:

- analyze the top level
- considering the whole system

However:

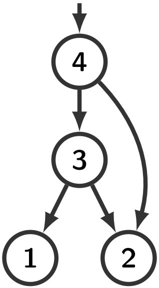
- complete system might be too complex
- changing subcomponents voids old results
- correctness of subcomponents is not addressed



Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents



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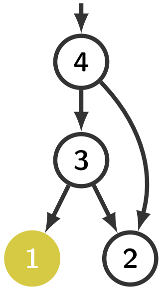

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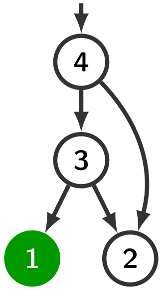

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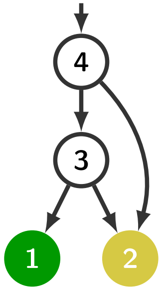

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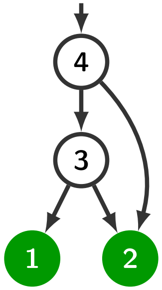

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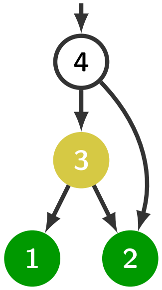

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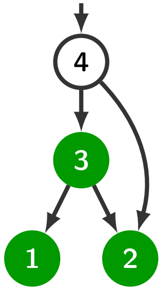

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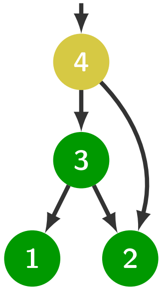

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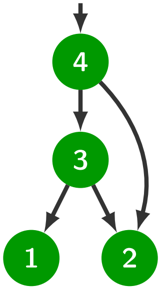

Modular Analysis

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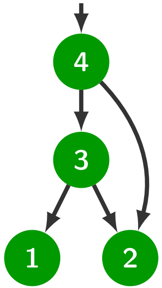
However:

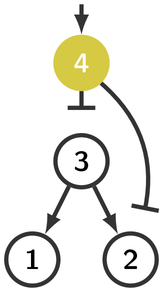
- changing subcomponents voids old results
- complexity can explode as we go up



Compositional Analysis

Compositional:

- analyze the top level
- abstracting subnodes by their contracts
- complexity of the system analyzed is reduced
- changing subcomponents preserves old results
  as long as new version respects contract



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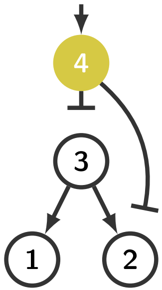
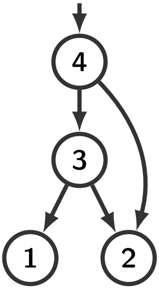


However:

- counterexamples might be spurious
- correctness of subcomponents is assumed

Compositional and Modular

Compositional and modular:



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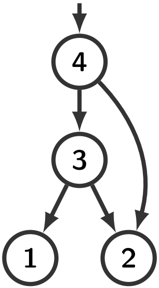

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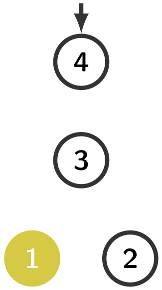

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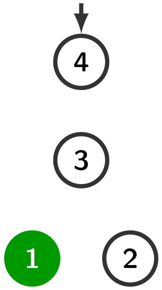

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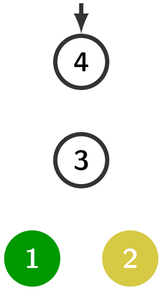

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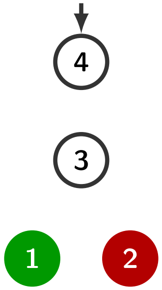

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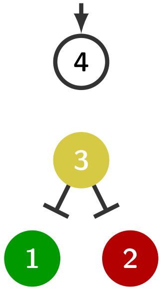

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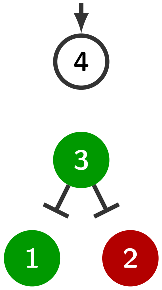

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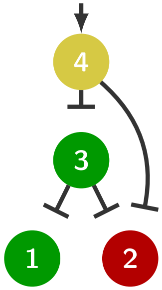

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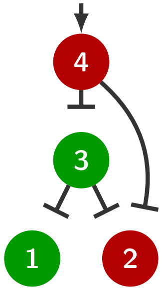

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Compositional and modular:

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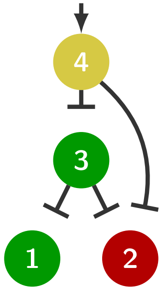
  In case of failure we can restart the analysis after refining by removing the abstraction, possibly repeatedly



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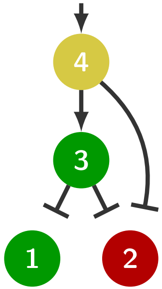

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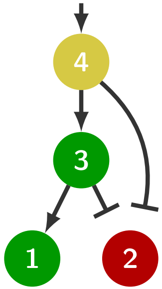
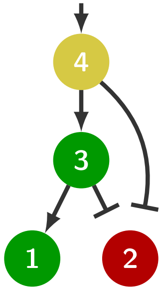


Compositional and Modular

Compositional and modular:

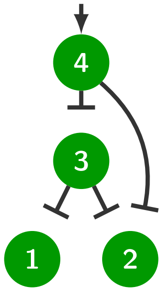
- no abstraction for the leaf components
- as we move up, we abstract subcomponents
  In case of failure we can restart the analysis
  after refining by removing the abstraction,
  possibly repeatedly
- all components are checked
- changing subcomponents preserves old results
  (as long as new versions are correct)
- results for subcomponents are reused
- refining identifies spurious counterexamples



Compositional and Modular: Benefits

If all components are valid, without refinement:

- the system as a whole is correct
- changing a component by a different, correct one does not impact the correctness of the whole system



Compositional and Modular: Benefits

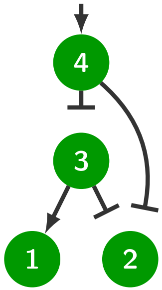
If all components are valid, with refinement:

- the system as a whole is correct
- but the contracts are not good enough for a compositional analysis to succeed

Refinement gives hints as to why

Compositional and Modular: Benefits

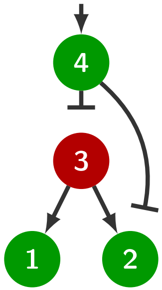
If we had to refine component 1 to prove 3 correct, that's probably because 1's contract is too weak



Compositional and Modular: Benefits

If after refining all sub-components we still cannot prove 3 correct, that's because

- the assumptions of 3 are too weak, and/or
- the guarantees of 3 do not hold



Modes

Often, specifications are *contextual (mode-based)*:

when/if this is the case, do that

Modes: Example

stopwatch(`toggle`, `reset`) $\to$ `count`

Assumption:

- reasonable input — $\neg(\texttt{reset} \wedge \texttt{toggle})$

Guarantee:

- output range — $\texttt{count} \geq 0$, initially 0

Modes:	require	ensure
• resetting	`reset`	`count` is 0
• running	$\neg\texttt{reset} \wedge \texttt{on}$	`count` increases by 1
• stopped	$\neg\texttt{reset} \wedge \neg\texttt{on}$	`count` does not change

Modes

Often, specifications are *contextual (mode-based)*:

when/if this is the case, do that

Assume-Guarantee contracts do not adequately capture this sort of specifications ...

... because modes are simply encoded as conditional guarantees

Solution

Represent modes explicitly in the contract

A mode consists of a *require* (`req`) and an ensure (`ens`) clause

- expresses a transient behavior
- corresponds to a guarantee `req` ⇒ `ens`

⇒ separation between global behavior (guarantees)
and transient behavior (modes)

Modes in Contract

A set of modes M can be added to a contract

Its semantics is an assume-guarantee pair $\langle \mathcal{A},\ \mathcal{G} \rangle$ with

$$\begin{aligned} \mathcal{A} &\equiv \bigvee_{m \in M} \texttt{req}_m \\ \mathcal{G} &\equiv \bigwedge_{m \in M} (\texttt{req}_m \Rightarrow \texttt{ens}_m) \end{aligned}$$

Note: $\texttt{req}_m$'s need not be mutually exclusive

Modes: Example

stopwatch(toggle, reset) $\rightarrow$ count

```
var on: bool = toggle -> (pre on and not toggle) or (not pre on and
 toggle) ;
```

Assumption:

- reasonable input — $\neg(\texttt{reset} \wedge \texttt{toggle})$

Guarantee:

- output range — $\texttt{count} \geq 0$, initially 0

Modes:	require	ensure
• resetting	reset	$\texttt{count} = 0$
• running	$\neg\texttt{reset} \wedge \texttt{on}$	count increases by 1
• stopped	$\neg\texttt{reset} \wedge \neg\texttt{on}$	count does not change

Modes: Advantages

Detect shortcomings in the specification:

- do the modes cover all situations the assumptions allow?
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Produce better feedback for counterexamples:

- indicate which modes are active at each step
- provide a mode-based abstraction of the concrete values
- abstraction is in terms of user-specified behaviors

CocoSpec Contracts for Lustre

A CocoSpec contract is

- a set of assumptions,
- a set of guarantees, and
- a set of modes

Can contain *internal* variables

It can use *specification* nodes

Can be *inlined* in a node or *stand-alone*

Stand-alone contracts can be imported and instantiated

Stand-alone Contract with Modes

```
contract stopwatch_spec(tgl, rst: bool) returns (c: int) ;
let
  var on: bool = tgl -> (pre on and not tgl) or (not pre on and tgl) ;

  assume not (rst and tgl) ;
  guarantee c = 0 -> c >= 0 ;

  mode resetting (
    require rst ; ensure c = 0 ; ) ;
  mode running (
    require not rst and on ; ensure c = (1 -> pre c + 1) ; ) ;
  mode stopped (
    require not rst and not on ; ensure c = (0 -> pre c) ; ) ;
tel

node stopwatch(toggle, reset: bool) returns (count: int) ;
(*@contract import stopwatch_spec(toggle, reset) returns (count) ; *)
let ... tel
```

Additional Features

In contracts, one can

- refer to modes in formulas (with `::<mode_name>`)
- call contract-free nodes

```
node count(b: bool) returns (count: int) ;
let
  count = (if b then 1 else 0) + (0 -> pre count) ;
tel

contract stopwatch_spec(tgl, rst: bool) returns (c: int) ;
let
  ...
  mode running (...) ;
  mode stopped (...) ;
  ...
  guarantee not (::running and ::stopped) ;
  guarantee count(::resetting) > 0  =>  c < count(true) ;
tel
```

Modes: Advantages

Defensive check:

- modes **must** cover all reachable states
- **may** be declared as mutually exclusive

Check performed on the spec, independently of the implementation

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- modes **must** cover all reachable states
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Check performed on the spec, independently of the implementation

Mode references:

- can refer to a mode directly as a propositional var
- can write more robust / trustworthy spec
- can express guarantees about the spec easily

Modes: Advantages

Mode reachability:

- modes provide a finite abstraction of component
  (abstract state at time i = set of modes active at time i)
- can explore graph of connected modes
- from the initial state (BMC style)
- to compare with user's understanding

Modes: Advantages

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Abstraction for counterexample (cex) traces:

- cex traces feature concrete values and can be hard to read
- we can annotate states with active modes
- therefore abstracting the states using user-provided information

Modes: Advantages

Test generation:

- can generate witnesses for abstract executions
- thus obtaining specification-based, implementation-agnostic test cases from the model

CocoSpec Support

CocoSpec is fully supported by Kind 2 model checker

Kind 2 [Champion et al., 2016b]:

- multi-engine SMT-based safety checker for Lustre models
- competitive with state-of-the-art checkers for infinite-state systems
- engines run concurrently and cooperatively
- can run modular / compositional, mode-aware analysis
- implements all the features discussed so far
- used at Rockwell Collins, GE, Peugeot, . . .

Case Study: Transport Class Model (TCM)

System developed by NASA Langley in Simulink [Brat et al., 2015]

Generic model of a mid-size, twin-engine transport aircraft [Hueschen, 2011]

System requirements elicited from Federal Avionic Regulations

Case Study: Transport Class Model (TCM)

We formalized in Lustre TCM's mode logic + autopilot controllers [Champion et al., 2016a]

- looks arbitrarily far in the past
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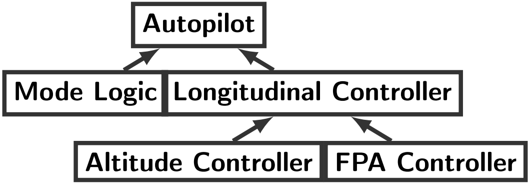
Hi-level architecture:



Case Study: Transport Class Model (TCM)

TCM formalization in CoCoSpec+Lustre and analysis with Kind 2

- Guessed contracts for subcomponents mostly by trial and error (auto-active model checking?)
- Mode-related feedback invaluable for us, not aviation experts, to specify TCM
- Additional contracts added to abstract non-linear arithmetic expressions
- Monolithic analysis unsuccessful after several hours
- Modular and compositional analysis successful on the whole subsystem (including non-linear exprs) in under 2 minutes

Conclusion

Mode-based Assume-Guarantee Contracts:

- more scalable verification thanks to compositional reasoning
- bring contract language closer to specification documents
- improve user feedback (blame assignment, abstract cex traces)
- raise trust in specification, improve maintainability, . . .
- enable specification-based test generation

http://kind.cs.uiowa.edu/

Thanks!

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