Bridging the Gap Between Requirements and Model Analysis: Evaluation on Cyber-Physical Challenge Problems

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Outline

Outline

Survey on Model-Based Software Engineering and Auto-Generated Code[1]

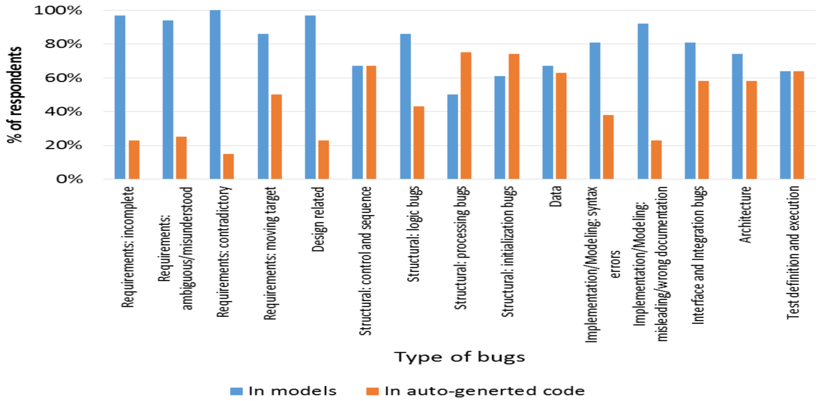


Figure: Types of bugs observed in the models and auto-generated code (responses to each part of question ranged from 11 to 35)

[1]NASA/TM-2016-219443

Introduction

Safety-critical development process

- High-level requirements are incrementally refined.
- Verification and validation at each level.
- Development process preserves the requirements.

Challenge

Difficult to make a formal connection between specifications and software artifacts.

Motivation

- Providing requirements written in restricted natural languages with formal semantic (FRET).
- Attaching system requirements to software artifacts (FRET-CoCoSim).
- Analyzing the model against those requirements (CoCoSim).

FRET

FRET: Formal Requirements Elicitation Tool

FRET is a framework for the elicitation, formalization, and understanding of requirements.

FRET Team

Anastasia Mavridou

Dimitra Giannakopoulou

Tom Pressburger

Johann Schumann

CoCoSim

CoCoSim: Contract based Compositional verification of Simulink models.

CoCoSim is an automated analysis and code generation framework for Simulink and Stateflow models.

CoCoSim Team

Hamza Bourbouh

Pierre-Loic Garoche

… and many others from
The University of Iowa,
Onera - France,
Khanh Trinh (NASA Ames)

FRET-CoCoSim workflow

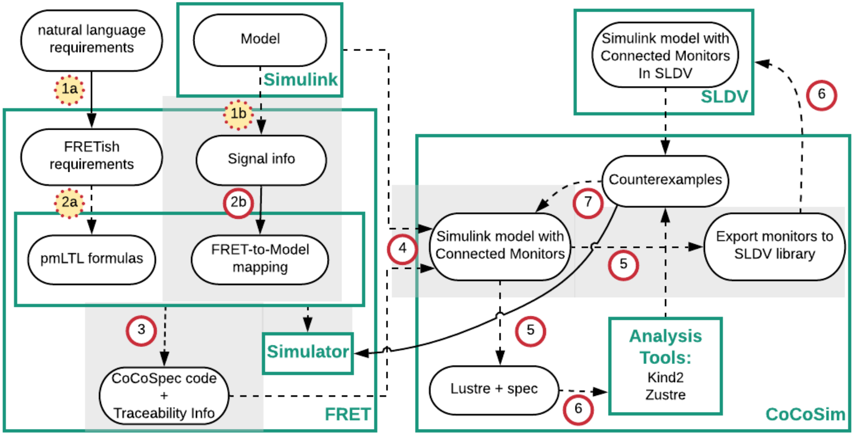

natural language requirements
1a
Model
Simulink
1b
FRETish requirements
Signal info
2a
2b
pmLTL formulas
FRET-to-Model mapping
3
Simulator
CoCoSpec code + Traceability Info
FRET
Simulink model with Connected Monitors In SLDV
SLDV
6
Counterexamples
7
4
Simulink model with Connected Monitors
5
Export monitors to SLDV library
5
Analysis Tools: Kind2 Zustre
Lustre + spec
6
CoCoSim

Figure: FRET-Workflow

Outline

FRET and Past Time Metric LTL

- Users enter system requirements in a restricted English-like natural language called FRETish.
- FRETish contains up to six fields: `scope`, `condition`, `component*`, `shall*`, `timing`, and `response*`. Mandatory fields are indicated with an asterisk.
  - `scope` field specifies the period where the requirement holds. If omitted, the requirement is deemed to hold universally.
  - `condition` field is a Boolean expression that further constrains when the requirement `response` shall occur.
  - `component` field specifies the component that the requirement refers to.
  - `timing` field specifies when the response shall happen. For instance: *immediately*, *always*, *after N time units*, etc.
  - `response` is either an action that the component must execute, or a Boolean condition that the component's behavior must satisfy.

Example

Syntax: `scope`, `component`, `shall`, `timing`, `response`

AP-002: In roll_hold mode RollAutopilot shall always satisfy autopilot_engaged & no_other_lateral_mode

FRET Output

For each requirement, FRET generates two LTL-based formalizations in:

1. pure Future Time Metric LTL; and
2. pure Past Time Metric LTL (we refer to it as pmLTL).

The syntax of the generated formulas is compatible with the **NuSMV** model checker.

Past Time Metric LTL

Past time operators (`Y, O, H, S`)

- `Y` (for '`Yesterday`'): At any non-initial time, `Y`f is true iff f holds at the previous time instant.
- `O` (for '`Once`'): `O`f is true iff f is true at some past time instant including the present time.
- `H` (for '`Historically`'): `H`f is true iff f is always true in the past.
- `S` (for '`Since`'): f`S`g is true iff g holds somewhere at point t in the past and f is true from that point on.

Past Time Metric LTL

Time-constrained versions of past time operators

$O_p \ [l, r] \ f$, where $O_p \in \{\mathtt{O}, \ \mathtt{H}, \ \mathtt{S}\}$ and $l, r \in \mathbb{N}^0$.

- $\mathtt{H} \ [l, r] \ f$ is true at time t iff f holds in *all* previous time instants t' such that $t - r \leq t' \leq t - l$.
- $\mathtt{O} \ [l, r] \ f$ is true at time t iff f was true in *at least one* of the previous time instants t' such that $t - r \leq t' \leq t - l$.
- $f \ \mathtt{S} \ [l, r] \ g$ is true at time t iff g holds at point t' in the past such that $t - r \leq t' \leq t - l$ and f is true from that point on.

Outline

Lustre synchronous dataflow language

- Lustre code consists of a set of *nodes* that transform infinite streams of *input* flows to streams of *output* flows.
- A symbolic "abstract" universal clock is used to model system progress
- Two important Lustre operators are
  - Right-shift `pre` (for `previous`) operator: at time $t = 0$, `pre` p is undefined, while for each time instant $t > 0$ it returns the value of p at $t - 1$. Example:

t	0	1	2	3
p	11	12	13	14
pre(p)	-	11	12	13

  - Initialization `->` (for followed-by) operator: At time $t = 0$, p `->` q returns the value of p at $t = 0$, while for $t > 0$ it returns the value of q at t.

t	0	1	2	3
x0	0	2	4	6
p	11	12	13	14
x0 -> pre(q)	0	11	12	13

Example of pmLTL operators in Lustre

- Historically

```
node H(X:bool) returns (Y:bool);
let
    Y = X -> (X and (pre Y));
tel
```

- Since

```
--Y S X
node S(X,Y: bool) returns (Z:bool);
let
Z = X or (Y and (false -> pre Z));
tel
```

- Once

```
node O(X:bool) returns (Y:bool);
let
 Y = X or (false -> pre Y);
tel
```

CoCoSpec

- CoCoSpec extends Lustre with constructs for the specification of assume-guarantee contracts.
- CoCoSpec assume-guarantee contracts are pairs of past time LTL predicates.
- A CoCoSpec contract can have:
  - internal variable declarations
  - `assume` (A) statements
  - `guarantee` (G) statements
  - `mode declarations` consist of `require` (R) and `ensure` (E) statements
- A node *satisfies* a contract $C = (A, G')$ if it satisfies $\mathtt{H}\ A \Rightarrow G'$, where $G' = G \cup \{R_i \Rightarrow E_i\}$.

Example: Stopwatch implementation

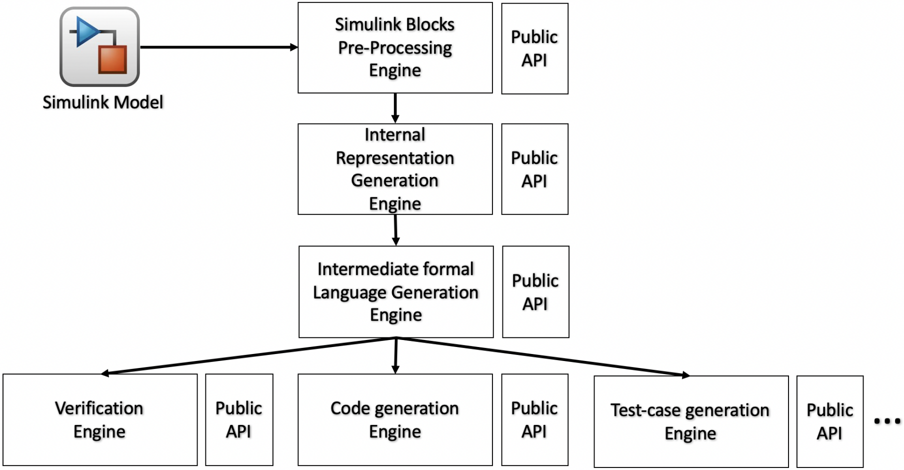
```
node stopwatch ( toggle , reset : bool ) returns (
   count : int );
(*@contract import stopwatchSpec(toggle , reset )
   returns (count) ; *)
var running : bool;
let
    running = (false -> pre running) <> toggle ;
    count =
        if reset then 0
        else if running then 1 -> pre count + 1
        else 0 -> pre count ;
tel
```

Example: Stopwatch Specification

```
contract stopwatchSpec( toggle, reset : bool ) returns
    ( time : int ) ;
let
  var on: bool = toggle -> (pre on and not toggle)
                          or (not pre on and toggle) ;
  assume not (toggle and reset) ;
  guarantee time >= 0 ;
  mode resetting (
    require reset ;
    ensure time = 0 ;
  );
  mode running (
    require (not reset) and on;
    ensure true -> time = pre time + 1 ;
  );
  mode stopped (
    require (not reset) and (not on) ;
    ensure true -> time = pre time ;
  ); tel
```

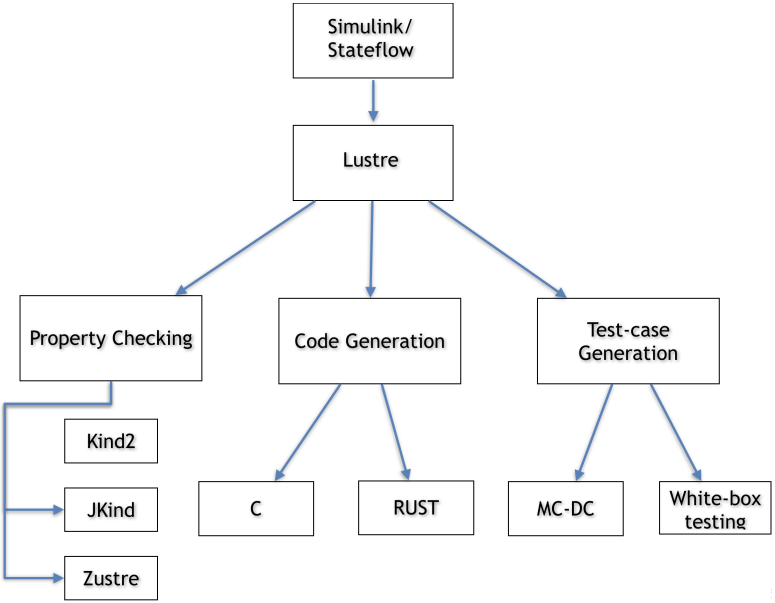
Outline

CoCoSim



Simulink Model
Simulink Blocks Pre-Processing Engine
Public API
Internal Representation Generation Engine
Public API
Intermediate formal Language Generation Engine
Public API
Verification Engine
Public API
Code generation Engine
Public API
Test-case generation Engine
Public API
...

CoCoSim


Simulink/ Stateflow
Lustre
Property Checking
Code Generation
Test-case Generation
Kind2
JKind
Zustre
C
RUST
MC-DC
White-box testing

CoCoSim: Unsupported blocks (1/4)

Library	# supp. Blocks	% supp. Blocks	Unsupported blocks
Discontinuities	11	91%	Backlash
Discrete	19	90%	Discrete PID Controller, Discrete PID Controller (2DOF)
Logic & Bit Operations.	18	95%	Extract Bits
Lookup Tables.	9	100%	
Math Operations.	31	83%	Algebraic Constraint, Complex to Magnitude-Angle, Complex to Real-Imag, Find, Magnitude-Angle to Complex, Real-Imag to Complex

CoCoSim: Unsupported blocks (2/4)

Library	# supp. Blocks	% supp. Blocks	Unsupported blocks
Model Verif.	11	100%	
Ports & Sub-systems.	29	93%	While Iterator Subsystem, While Iterator
Signal Att.	13	93%	Unit Conversion
Signal Routing.	13	52%	Data Store Memory/Read-/Write, Env. Controller, Goto Tag Visibility, Index Vector, State Reader, State Writer, Variant Source, Variant Sink, Manual Variant Source, Manual Variant Sink

CoCoSim: Unsupported blocks (3/4)

Library	# supp. Blocks	% supp. Blocks	Unsupported blocks
Sinks.	9	100%	
Sources.	15	57%	Band-Limited White Noise, Counter Free-Running, Counter Limited, From File, From Spreadsheet, Repeating Sequence, Repeating Sequence Interpolated, Repeating Sequence Stair, Signal Editor, Signal Generator, Waveform Generator

CoCoSim: Unsupported blocks (4/4)

Library	# supp. Blocks	% supp. Blocks	Unsupported blocks
User-Defined Functions.	1	6%	Argument Inport, Argument Outport, Event Listener, Function Caller, Initialize Function, MATLAB Function, Interpreted MATLAB Function, Level-2 MATLAB S-Function, MATLAB System, Reset Function, S-Function, S-Function Builder, Simulink Function, Terminate Function

Outline

Lockheed Martin Challenge Problems

- LM Aero Developed Set of 10 V&V Challenge Problems
- Each challenge includes:
  - Simulink model
  - Parameters
  - Documentation Containing Description and Requirements
- Difficult due to transcendental functions, nonlinearities and discontinuous math, vectors, matrices, states
- Challenges built with commonly used blocks
- Publicly available case study. The challenges can be found in `https://github.com/hbourbouh/lm_challenges`

Overview of Challenge Problems

- Triplex Signal Monitor
- Finite State Machine
- Tustin Integrator
- Control Loop Regulators
- NonLinear Guidance Algorithm
- Feedforward Cascade Connectivity Neural Network
- Abstraction of a Control (Effector Blender)
- 6DoF with DeHavilland Beaver Autopilot
- System Safety Monitor
- Euler Transformation

Type of Simulink blocks used in the Challenges

Some of the blocks make verification difficult due to:

- **Transcendental Functions**: Such as the trigonometric functions. Challenge 7 (AP) uses *cos*, *sin*, *atan2*, *asin*. Challenge 9 (EUL) uses *sin* and *cos*.
- **Nonlinearities and Discontinuous Math**: Such as *Abs*, *MinMax*, *Saturation*, *Switch*. Inverse of Matrix (3 by 3 and 5 by 5 Matrices) are used in Challenge 6 (EB) and 7 (AP).
- **Multidimensional Arrays**: Challenges 6 (EB) and 7(AP) use the inverse of matrices, which is abstracted in Lustre. Additionally, challenge 7 (AP) manipulates Quaternions with some advanced *Quaternion* operations (e.g. *Quaternion Modulus*, *Quaternion Norm* and *Quaternion Normalize*).
- **States**: Blocks such as *Delay* and *Unit Delay* are used in the majority of LMCPS. They are used to access memories of signals up to n steps back (n=1 for UnitDelay).

Type of Simulink blocks used in the Challenges

Model	# Blocks	Block Types used
0_triplex	479	'**Abs**', 'Action Port', 'Constant', '**Delay**', 'Demux', 'From', 'Goto' '**If**', 'Inport', '**Logic**', '**Merge**', 'Mux', 'Outport', '**Product**', '**Relational Operator**', '**Selector**', 'Signal Conversion', 'Subsystem', '**Sum**', '**Switch**', 'Terminator'
1_fsm	279	'Action Port', 'Constant', 'Demux', 'From', 'Goto', '**If**', 'Inport', '**Logic**', '**Merge**', 'Mux', 'Outport', '**Relational Operator**', '**Signal Conversion**', 'Subsystem', '**Switch**', '**Unit Delay**'

Type of Simulink blocks used in the Challenges

Model	# Blocks	Block Types used
2_tustin	45	'DataType Duplicate', 'Data Type Propagation', 'From', 'Gain', 'Goto', 'Inport', 'Outport', '**Product**', '**Relational Operator**', '**Saturation Dynamic**', 'Subsystem', '**Sum**', '**Switch**', '**Unit Delay**'
3_regulators	271	'**BusCreator**', '**BusSelector**', 'Constant', 'From', 'Gain', 'Goto', 'Inport', '**Lookup_nD**', '**Math**', '**Memory**', 'Outport', '**Product**' '**Relational Operator**', '**Saturate**', '**Saturation Dynamic**', '**Signal Conversion**', 'SubSystem', 'Sum', '**Switch**', 'Terminator', '**UnitDelay**'

Type of Simulink blocks used in the Challenges

Model	# Blocks	Block Types used
4_nlguide	355	'ActionPort', 'Constant', 'Demux', 'Display', '**DotProduct**', 'From', '**Gain**', 'Goto', '**If**' , 'Inport', 'InportShadow', '**Logic**', '**Math**', '**Merge**', 'Mux', 'Outport', '**Product**', '**Relational Operator**', '**Selector**', '**Sqrt**', 'SubSystem', '**Sum**', 'Terminator'
5_nn	699	'ActionPort', 'Constant', 'Demux', '**Gain**', '**If**', 'Inport', '**Merge**', 'Mux', 'Outport', '**Product**', '**Saturate**', 'SubSystem', '**Sum**'
6_eb	75	'Constant', 'Display', 'Inport', '**Math**', 'Outport', '**Product**', '**Relational Operator**', '**Reshape**', '**Selector**', 'SubSystem', '**Sum**', '**Switch**'

Type of Simulink blocks used in the Challenges

Model	# Blocks	Block Types used
7_autopilot	1357	'**Abs**', '**BusCreator**', '**BusSelector**', '**Concatenate**', 'Constant', '**Data Type Conversion**', 'Demux', 'Display', '**DotProduct**', '**Fcn**', 'From', '**Gain**', 'Goto', 'Ground', 'Inport', 'InportShadow', '**Logic**', '**Lookup_nD**', '**Math**', '**MinMax**', 'Mux', 'Outport', '**Product**', '**RateLimiter**', '**Relational Operator**', '**Reshape**', '**Rounding**', '**Saturate**', 'Scope', '**Selector**', '**Signum**', '**Sqrt**', 'SubSystem', 'Sum', '**Switch**', 'Terminator', '**Trigonometry**', '**UnitDelay**', '**CMBlock**', '**Create 3x3 Matrix**', '**Passive**', '**Quaternion Modulus**', '**Quaternion Norm**', '**Quaternion Normalize**', 'Rate Limiter Dynamic'

Type of Simulink blocks used in the Challenges

Model	# Blocks	Block Types used
8_swim	141	'ActionPort', 'Constant', 'Display', '**Gain**', '**If**', 'Inport', '**Logic**', '**Merge**', 'Outport', '**Relational Operator**', '**Sqrt**', 'SubSystem', '**Sum**', '**UnitDelay**'
9_euler	97	'**Concatenate**', '**Fcn**', 'Inport', 'Mux', 'Outport', '**Product**', '**Reshape**', 'SubSystem', '**Trigonometry**', '**Create 3x3 Matrix**'

Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is not in control (not **standby**) and the system is **supported** without failures (not **apfail**).

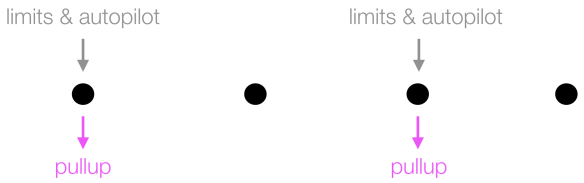
Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.

autopilot = !standby & !apfail & supported

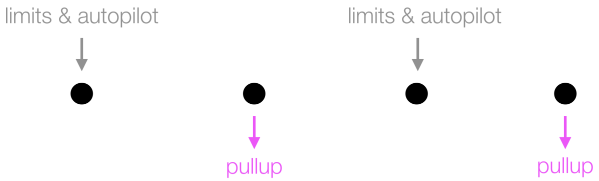
Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.

First interpretation:

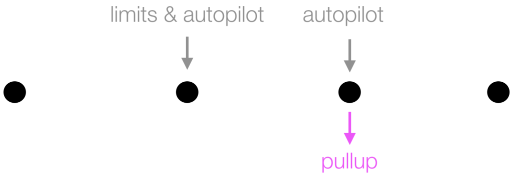


Second interpretation:



Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.
Third interpretation: Does autopilot should stay active when latching a pullup?



Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.

First interpretation:

FSM shall always satisfy (limits & autopilot) => pullup

((limits & autopilot) => pullup) S (((limits & autopilot) => pullup) & FTP)

```
contract FSMSpec(apfail:bool; limits:bool; standby:bool;
    supported:bool; ) returns (pullup: bool; );
let
var FTP:bool=true -> false;
var autopilot:bool=supported and not apfail and not standby;
guarantee "FSM001" S( (((limits and autopilot) => (pullup))
    and FTP), ((limits and autopilot) => (pullup)));
tel
```

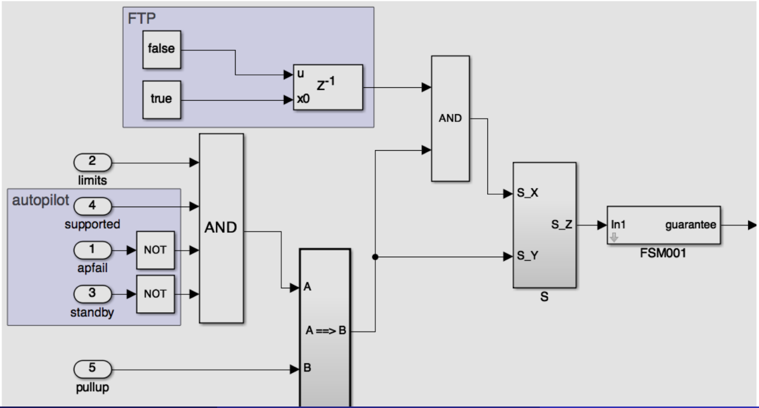
Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.

First interpretation:

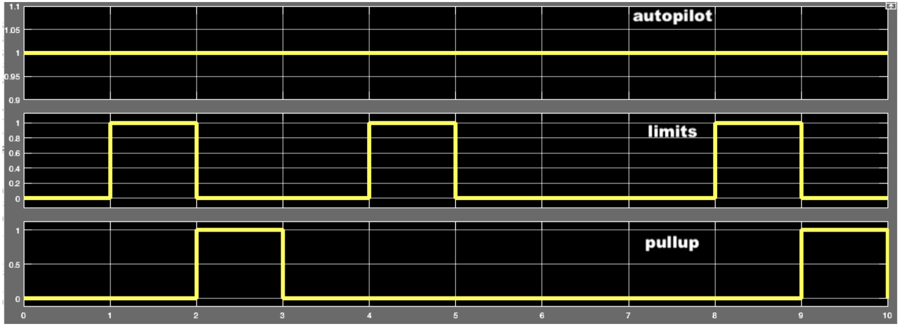
FSM shall always satisfy (limits & autopilot) => pullup

((limits & autopilot) => pullup) S (((limits & autopilot) => pullup) & FTP)

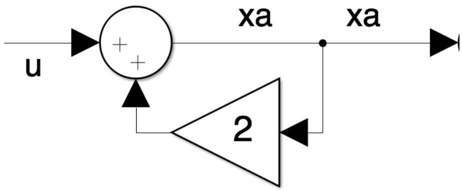


Finite State Machine Requirement Example

Exceeding sensor **limits** shall latch an autopilot **pullup** when the pilot is in **autopilot**.



Algebraic loop



Example of an algebraic loop accepted by Simulink.

```
xa = u + 2*xa;
```

The generated Lustre that will be rejected because of the circular dependency.

Figure: A simple example of an algebraic loop.

6DOF with DeHavilland Beaver Autopilot

Examples of requirements we needed domain expert help.

- **AP-004a:** Steady state roll commands shall be tracked within 1 degree in calm air.
- **AP-004b:** Response to roll step commands shall not exceed 10% overshoot in calm air.

Example of a requirement we could not formalize.

- **AP-004c:** Small signal ($<$3 degree) roll bandwidth shall be at least 0.5 rad/sec.

Challenge Problem Analysis Results

				Kind2	SLDV
Name	# Req	# Form	# An	V/IN/UN	V/IN/UN
Triplex Monitor	6	6	6	5/1/0	5/1/0
FSM	13	13	13	7/6/0	7/6/0
Tustin Integrator	4	3	3	2/0/1	2/0/1
Regulators	10	10	10	0/5/5	0/0/10
Feedforward NN	4	4	4	0/0/4	0/0/4
Effector Blender	4	3	3	0/0/3	0/0/0
6DoF Autopilot	14	13	8	5/3/0	4/0/4
Sys. Safety Monitor (SWIM)	3	3	3	2/1/0	0/1/2
Euler Transf.	8	7	7	2/5/0	1/0/6
Total	66	62	57	23/21/13	19/8/27

Outline

Lessons learned

- Domain expertise is needed
- Frequently used patterns: used only 8/120 FRET patterns, mainly invariants
- Incomplete Requirements: requirements were not mutually exclusive
- Scalability of the approach: tool-set keeps model hierarchy, contracts deployed at different levels
- Comparison of analysis tools: Kind2 faster usually than SLDV, also returned results in more cases due to modular analysis

Lessons learned

- Reasoning for violated properties: two ways

$$H(A => B)$$

  - Check a weaker property by strengthening the preconditions $A' \subset A$ and check $H(A' => B)$
  - Check feasibility of B with bounded model checking $H(\neg B)$ and return counterexamples to help construct stronger preconditions for which B is satisfied

Outline

Our work supports...

- Automatic extraction of Simulink model information
- Association of high-level requirements with target model signals and components
- Translation of temporal logic formulas into synchronous data flow specifications and Simulink monitors
- Interpretation of counterexamples both at requirement and model levels

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