FRET Tutorial

Formal Requirements Elicitation Tool

Presented by

Tom Pressburger

May 02, 2022

Lockheed Martin Cyber-Physical System Challenge, component FSM

The 10 Cyber-Physical V&V Challenges were created by Lockheed Martin Aeronautics to evaluate and improve the state-of-the-art in formal method toolsets. Each challenge problem includes:

a high-level description

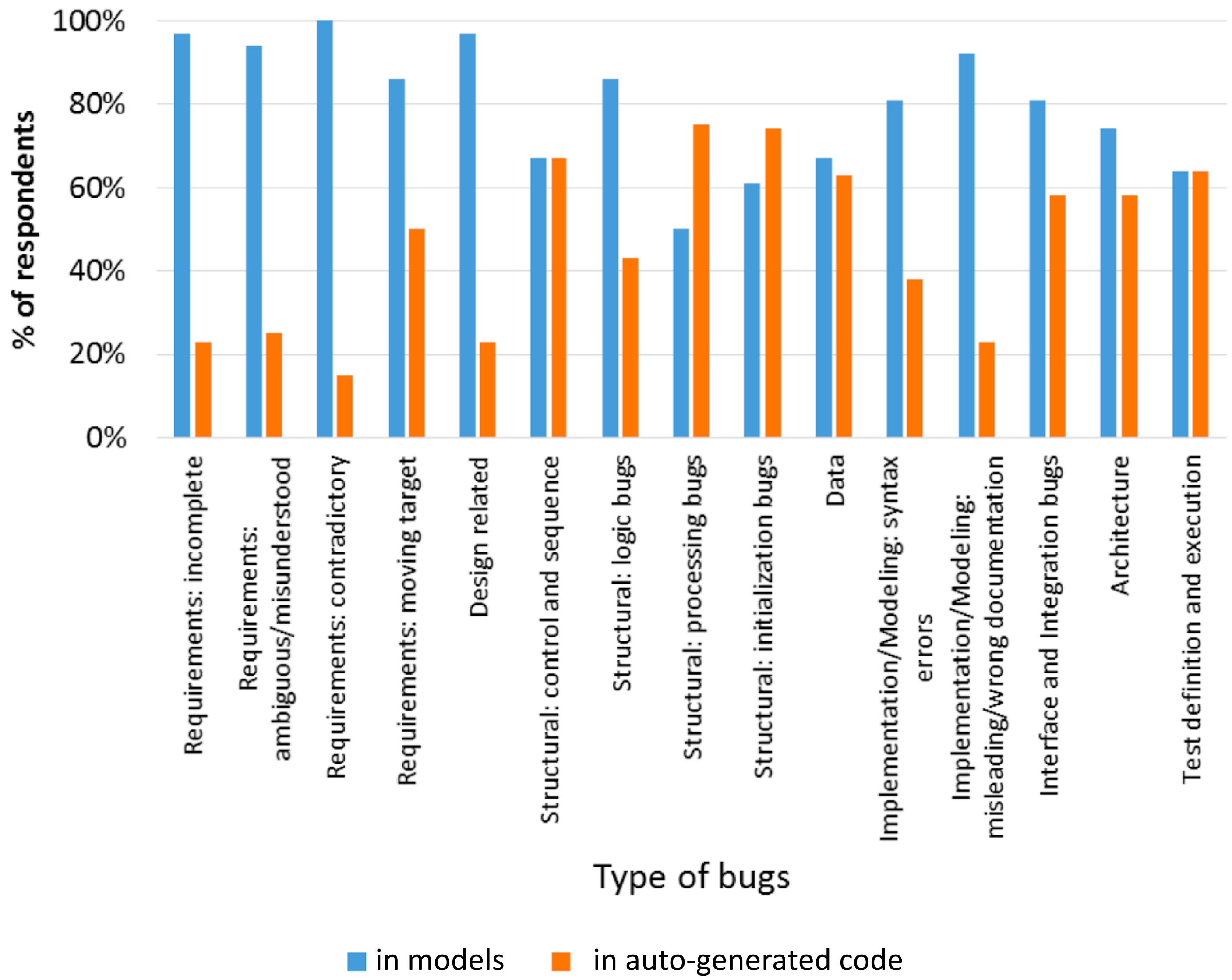
a set of requirements written in plain English;

a Simulink model;

a set of parameters (in .mat format) for simulating the model.

FSM: represents an abstraction of an advanced autopilot system responsible for commanding a safety maneuver in the event of a hazard.

What types of bugs are found in models and code?



Johann Schumann, Matt Knudsen, Teme Kahsai, Noble Nkwocha, Katerina Goseva-Popstojanova, Thomas Kyanko, "Report: Survey on Model-Based Software Engineering and Auto-Generated Code", NASA/TM-2016-219443, 2016.

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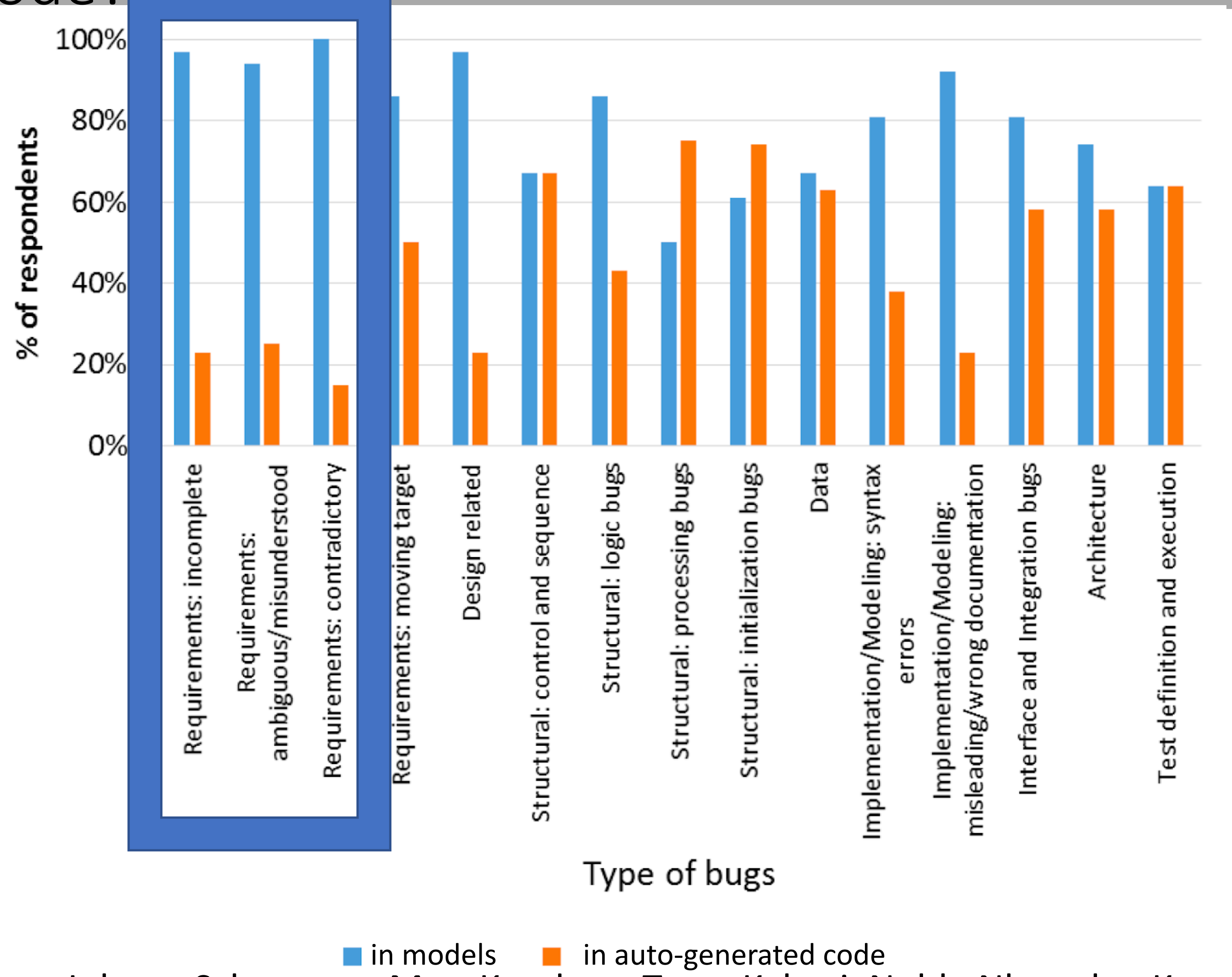

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language of developers forced to write reqs

- 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).
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- …

Are the requirements consistent?

Does my model/code satisfy the requirements?

language formal analysis tools understand

```
var autopilot: bool = (not standby) and supported and (not
   apfail);
var pre_autopilot: bool = false -> pre autopilot;
var pre_limits: bool = = false -> pre limits;
guarantee "FSM-001v2" S((((((autopilot and pre_autopilot and
   pre_limits) and (pre ( not (autopilot and pre_autopilot and
   pre_limits)))) or ((autopilot and pre_autopilot and
   pre_limits) and FTP)) => (pullup)) and FTP), ((((autopilot
   and pre_autopilot and pre_limits) and (pre ( not (autopilot
   and pre_autopilot and pre_limits)))) or ((autopilot and
   pre_autopilot and pre_limits) and FTP)) => (pullup)));
```

FRET's mission is to provide an intuitive platform for capturing precise requirements, to serve as a portal to a variety of analysis tools, and to support requirements repair based on analysis feedback.

Welcome to FRET

https://github.com/NASA-SW-VnV/fret

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andreas.katis@nasa.gov
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Team (ARC): Andreas Katis, Anastasia Mavridou, Tom Pressburger, Johann Schumann, Khanh Trinh

Alumni: David Bushnell, Tanja DeJong, Dimitra Giannakopoulou, George Karamanolis, David Kooi, Julian Rhein, Nija Shi

Collaborators (LaRC): Swee Balanchandran, Esther Conrad, Aaron Dutle, Alwyn Goodloe, Ivan Perez, Laura Titolo

FRET bridges the gap

- Captures requirements in a restricted natural language with unambiguous semantics
- Explains formal semantics in various forms: natural language, diagrams, interactive simulation
- Assists in writing requirements through requirement templates
- Formalizes requirements in a compositional (hence maintainable and extensible) manner
- Checks consistency of requirements and provides feedback
- Connects with analysis tools and exports verification code
  - ✓ for model checking Simulink models with CoCoSim
  - ✓ for model checking Lustre code with Kind2
  - ✓ for efficient runtime monitoring with Copilot

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capturing requirements in FRETish

the altitude hold autopilot shall maintain altitude whenever altitude hold is selected

if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude

scope | condition | component | timing | response

capturing requirements in FRETish

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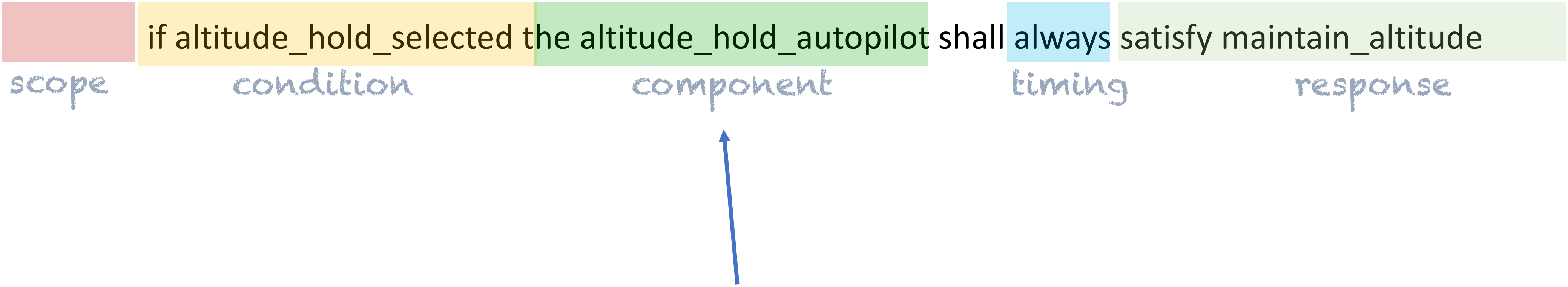

Q: Upon which part of the system is the requirement being levied?
A: The altitude_hold_autopilot.

capturing requirements in FRETish

the altitude hold autopilot shall maintain altitude whenever altitude hold is selected

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scope | condition | component | timing | response

Q: What do we want the system to achieve?
A: maintain_altitude

capturing requirements in FRETish

the altitude hold autopilot shall maintain altitude whenever altitude hold is selected

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scope | condition | component | timing | response

Q: During what portion of the execution is the requirement enforced?
A: It has been omitted, meaning *globally, always*
Note: the portion can be expressed relative to a system mode.

capturing requirements in FRETish

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if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude

scope | condition | component | timing | response

Q: What condition triggers the response?
A: altitude_hold_selected becoming true, within the scope

capturing requirements in FRETish

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if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude

scope | condition | component | timing | response

Q: Where does the response happen, relative to the scope and trigger?
A: always, meaning *thenceforth*

capturing requirements in FRETish

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scope	condition	component		timing	response
	if altitude_hold_selected	the altitude_hold_autopilot	shall	always	satisfy maintain_altitude

SCOPE	in, before, after, notin, onlyIn, onlyBefore, onlyAfter; when omitted, global
CONDITION	null, regular
TIMING	immediately, next, always, never, eventually, until, before, for, within, after
RESPONSE	satisfaction

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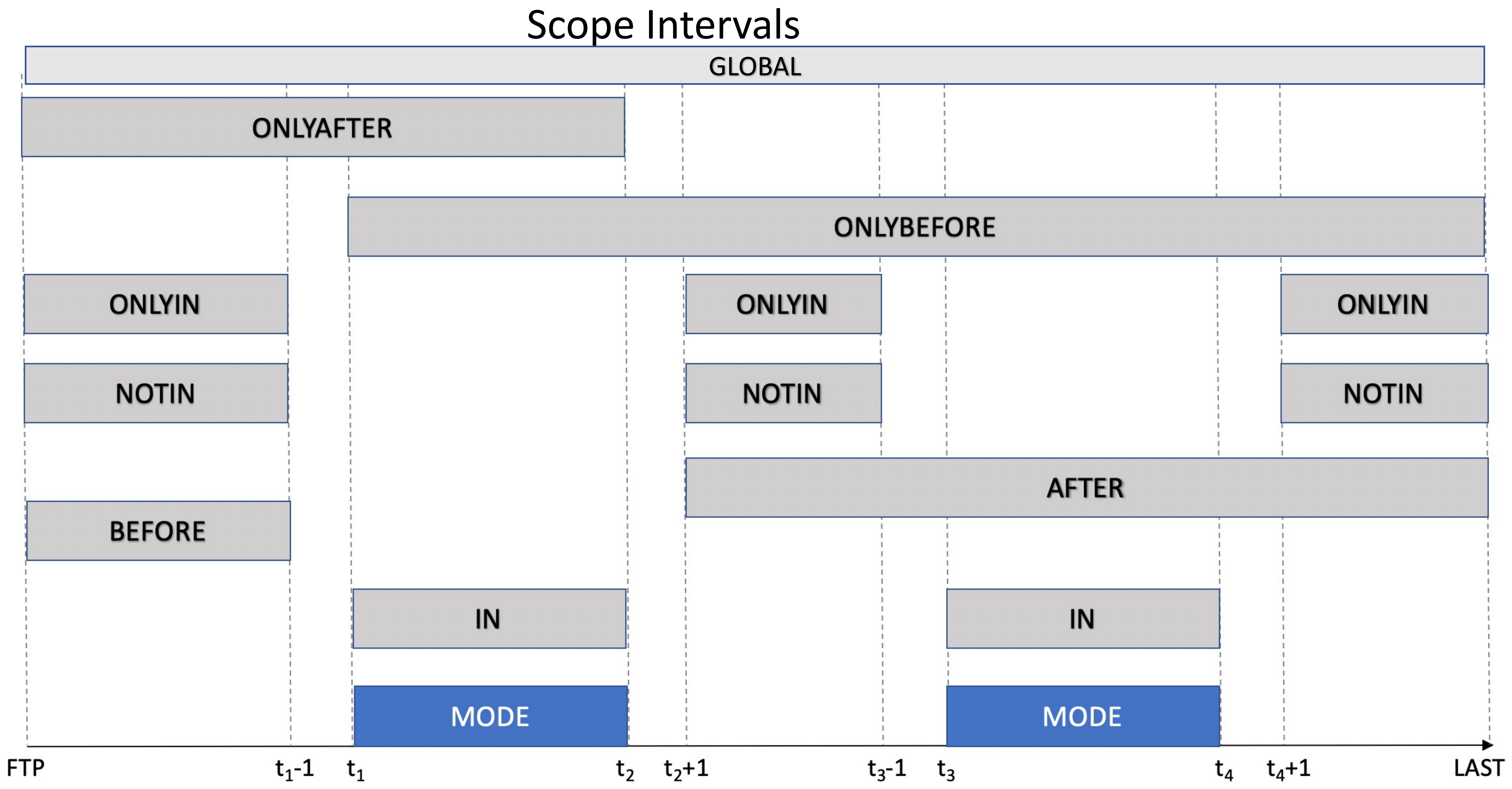
8 * 2 * 10 = 160 semantic templates / template keys!

Expressions

- Boolean
  - !, &, |, =>, *if _then _,* <=>, p(x,y,z)
  - *preBool(init,p),*
  - *persisted(n,p), occurred(n,p)*
  - *persists(n,p), occurs(n,p)*
- Arithmetic
  - =, !=, <, >, <=, >=
  - +, -, *, /, ^, f(x,y)
  - *preInt(init,n), preReal(init,x)*

Scope condition component timing response

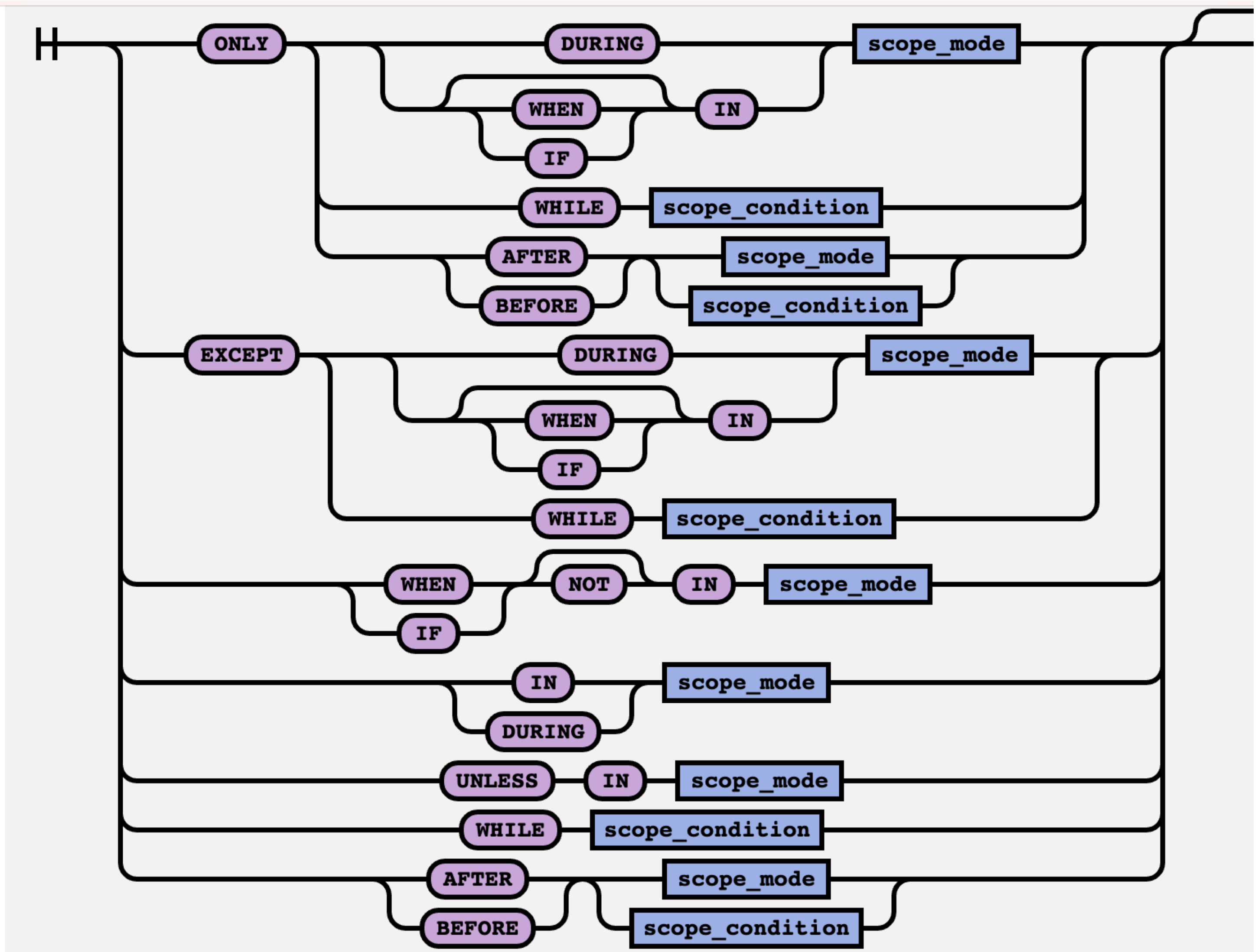
- **(global)** The system shall always satisfy count >= 0
- **In** landing mode the system shall eventually satisfy decrease_speed
- **Before** energized mode the system shall always satisfy energized_indicator_off
- **After** boot mode the system shall immediately satisfy prompt_for_password
- When **not in** initialization mode the system shall always satisfy commands_accepted
- **Only in** landing mode shall the system eventually satisfy landing_gear_down
- **Only before** energized mode shall the system eventually satisfy manually_touchable
- **Only after** arming mode shall the system eventually satisfy fired


Scope Intervals
GLOBAL
ONLYAFTER
ONLYBEFORE
ONLYIN
ONLYIN
ONLYIN
NOTIN
NOTIN
NOTIN
AFTER
BEFORE
IN
IN
MODE
MODE
FTP
t1-1
t1
t2
t2+1
t3-1
t3
t4
t4+1
LAST

Scope (contd)

- **While** mode = 4 the watch shall always satisfy alarm_icon_on
- **While** persisted(4,high_temperature) the monitor shall until shutoff satisfy alarm_on
- **Before** taxiing & receivedClearance the plane shall never satisfy takeoff

Scope grammar

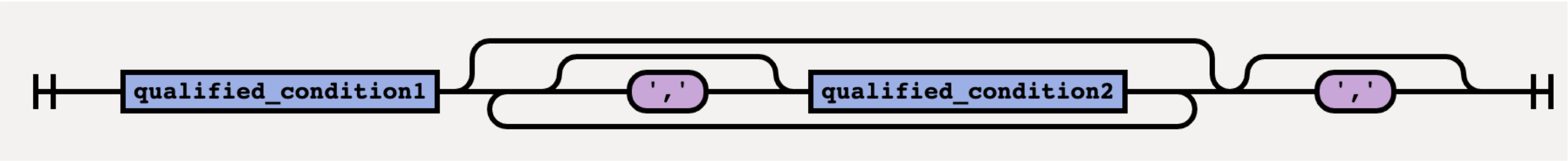


scope Condition component timing response

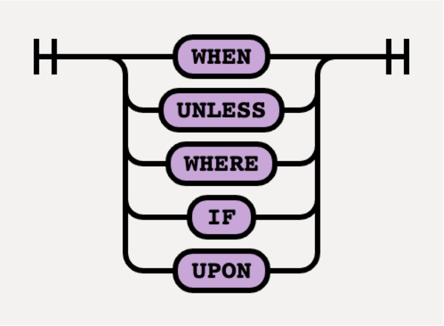
- *upon, if, when, where BOOL_EXP*
- *unless BOOL_EXP (equivalent to “upon ! BOOL_EXP”)*
- Trigger: **upon** the Boolean expression becoming true from being false in the scope, or being true at the beginning of the scope.

Condition grammar

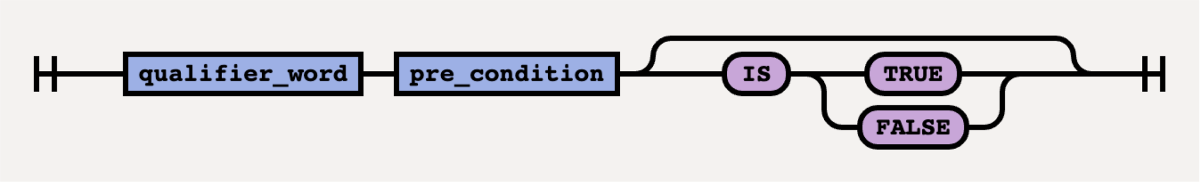
regular_condition



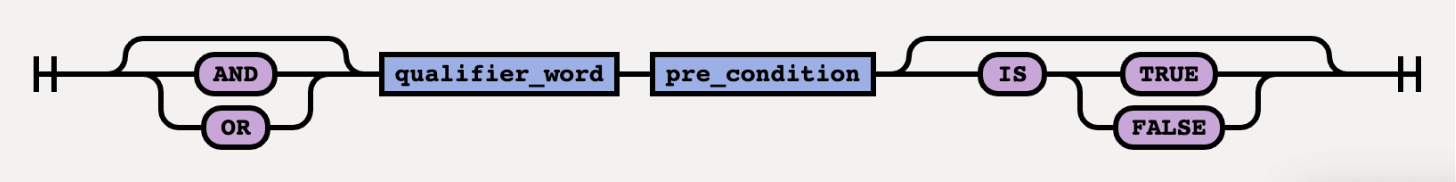
qualifier_word



qualified_condition1



qualified_condition2

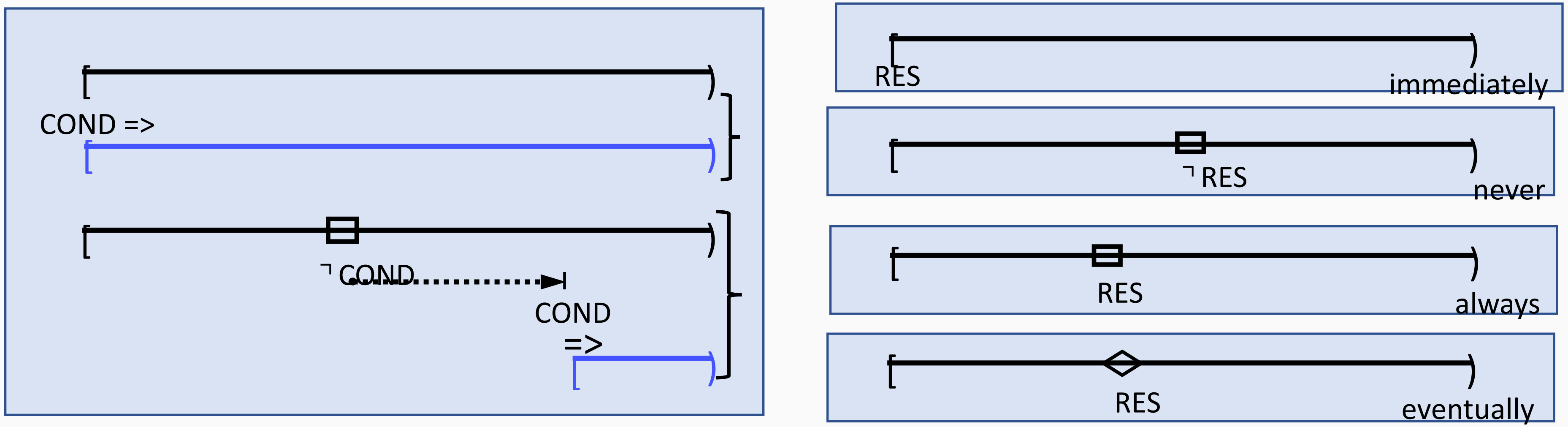


scope condition component Timing response

- In roll_hold mode RollAutopilot shall **immediately** satisfy if (roll_angle< 6.0 & roll_angle > -6.0) then roll_hold_reference = 0.0
- When currentOverload the circuitBreaker shall, at the **next** timepoint, satisfy shutoff
- In landingMode the system shall **eventually** satisfy LandingGearLowered
- The autopilot shall **always** satisfy if allGood then state = nominal
- In drivingMode the system shall **never** satisfy cellPhoneOn & !cellPhoneHandsFree
- When errorCondition, the system shall, **for** 4 ticks, satisfy alarmOn
- In landing mode, the the system shall **within** 2 ticks satisfy is_stable
- When input = 1, the integrator shall, **after** 10 ticks, satisfy output = 10
- In CountdownMode the system shall, **until** Count = 0, satisfy Count > 0
- The system shall, **before** TakeOff, satisfy CheckListTasksCompleted

FRET is rigorous and extensible

- Semantic templates have RTGIL semantics. RTGIL = Real-Time Graphical Interval Logic
- FRET generates formulas in *future*- (finite and infinite-trace) and *past*-time linear-time metric temporal logics, and CoCoSpec/Lustre. Discrete time.
- A verification framework within FRET ensures correctness of formalization algorithms.
- All aspects of our approach are compositional – based on requirement fields.



Dimitra Giannakopoulou, Thomas Pressburger, Anastasia Mavridou, Johann Schumann:
"Automated Formalization of Structured Natural Language", *Information and Software Technology*, 2021

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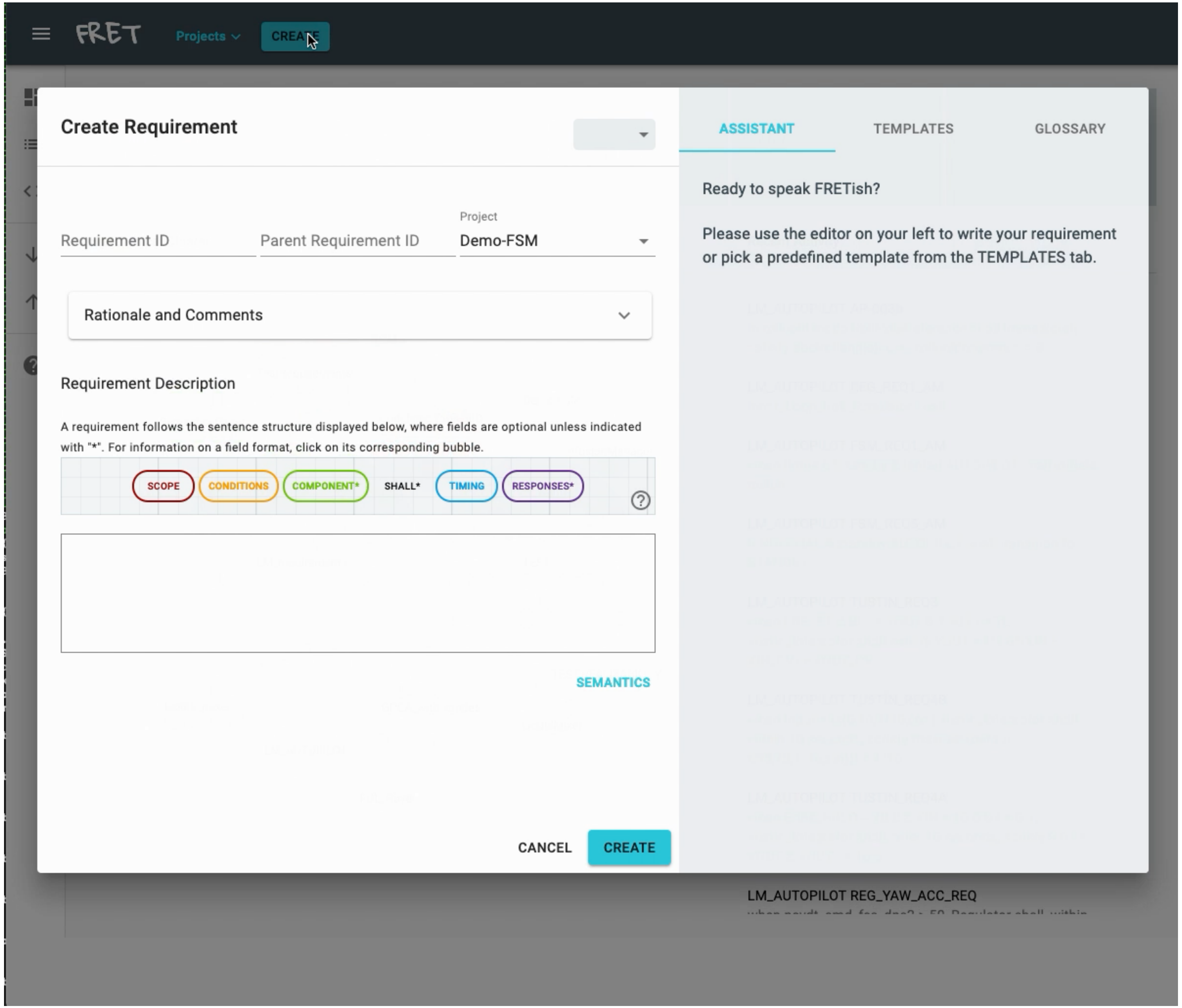
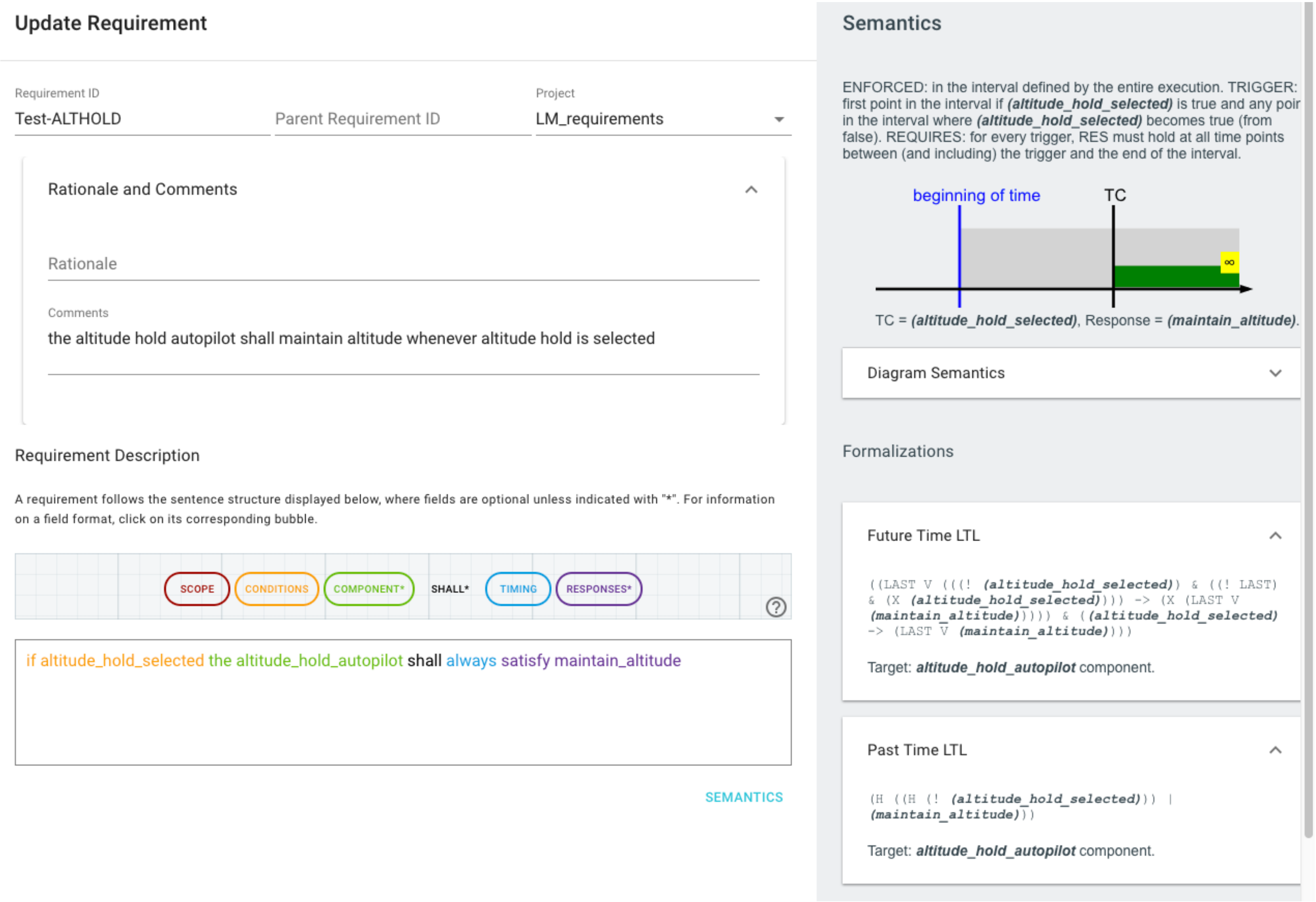
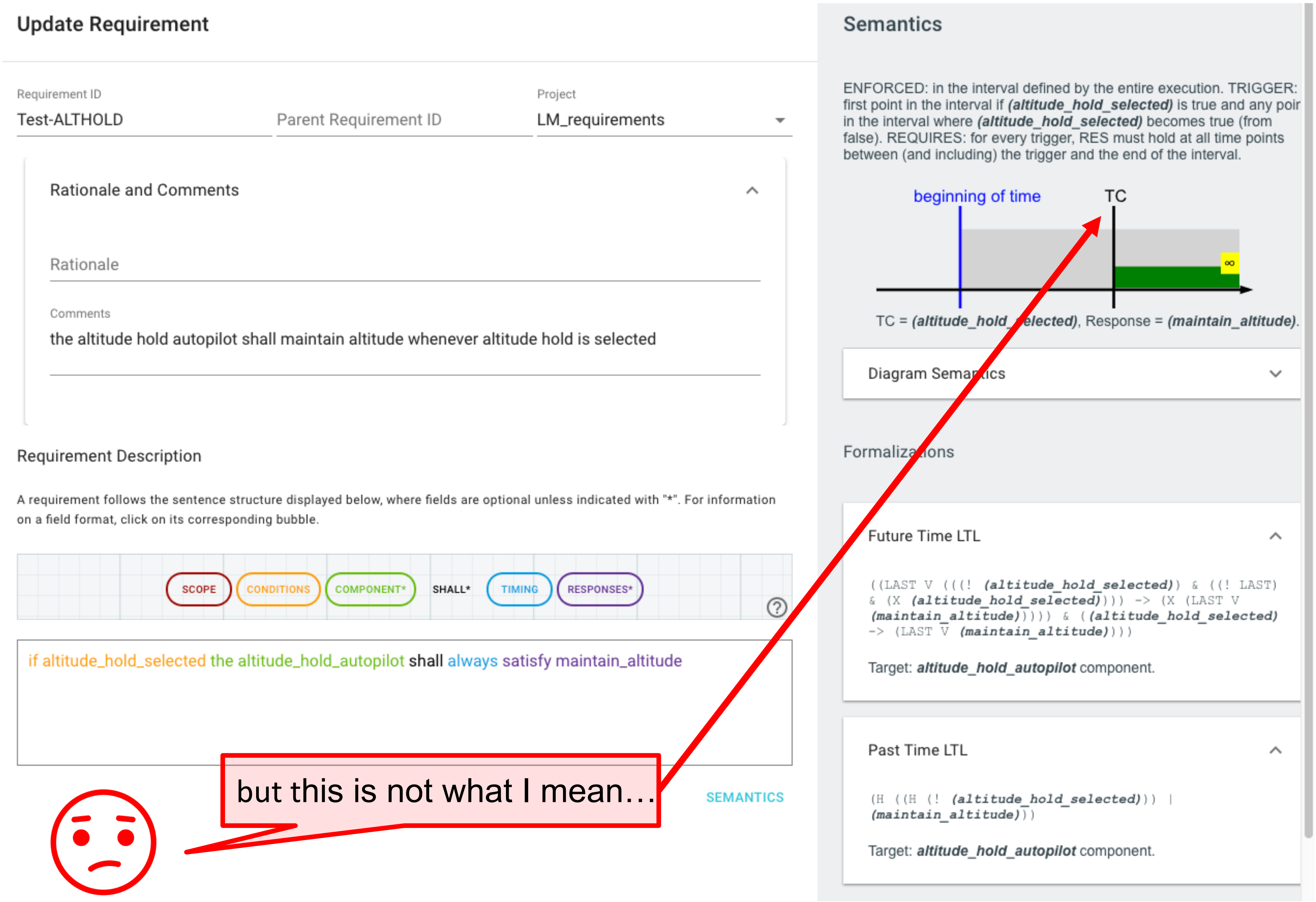
Capturing, explaining and formalizing requirements





Update Requirement
Requirement ID
Test-ALTHOLD
Parent Requirement ID
Project
LM_requirements
Rationale and Comments
Rationale
Comments
the altitude hold autopilot shall maintain altitude whenever altitude hold is selected
Requirement Description
A requirement follows the sentence structure displayed below, where fields are optional unless indicated with "*". For information on a field format, click on its corresponding bubble.
SCOPE
CONDITIONS
COMPONENT*
SHALL*
TIMING
RESPONSES*
if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude
SEMANTICS
Semantics
ENFORCED: in the interval defined by the entire execution. TRIGGER: first point in the interval if (altitude_hold_selected) is true and any poir in the interval where (altitude_hold_selected) becomes true (from false). REQUIRES: for every trigger, RES must hold at all time points between (and including) the trigger and the end of the interval.
beginning of time
TC
∞
TC = (altitude_hold_selected), Response = (maintain_altitude).
Diagram Semantics
Formalizations
Future Time LTL
((LAST V (((! (altitude_hold_selected)) & ((! LAST) & (X (altitude_hold_selected)))) -> (X (LAST V (maintain_altitude))))) & ((altitude_hold_selected) -> (LAST V (maintain_altitude))))
Target: altitude_hold_autopilot component.
Past Time LTL
(H ((H (! (altitude_hold_selected))) | (maintain_altitude)))
Target: altitude_hold_autopilot component.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but this is not what I mean…
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getting to the right requirement

TAKE1: if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude

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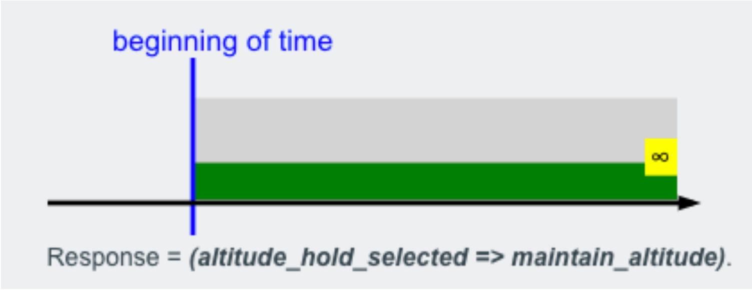
TAKE1: if altitude_hold_selected the altitude_hold_autopilot shall always satisfy maintain_altitude

TAKE2: the altitude_hold_autopilot shall always satisfy if altitude_hold_selected then maintain_altitude



getting to the right requirement

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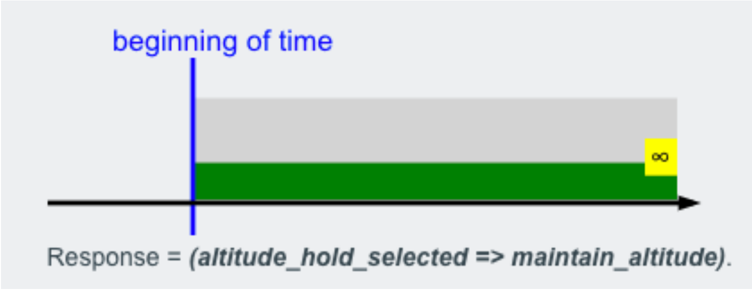
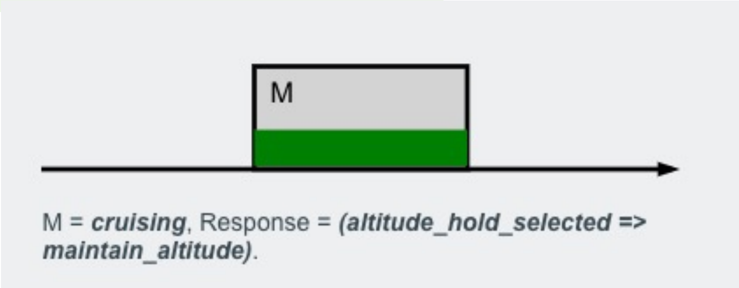


TAKE3: when in cruising mode, the altitude_hold_autopilot shall always satisfy if altitude_hold_selected then maintain_altitude



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Assistance: Requirement templates

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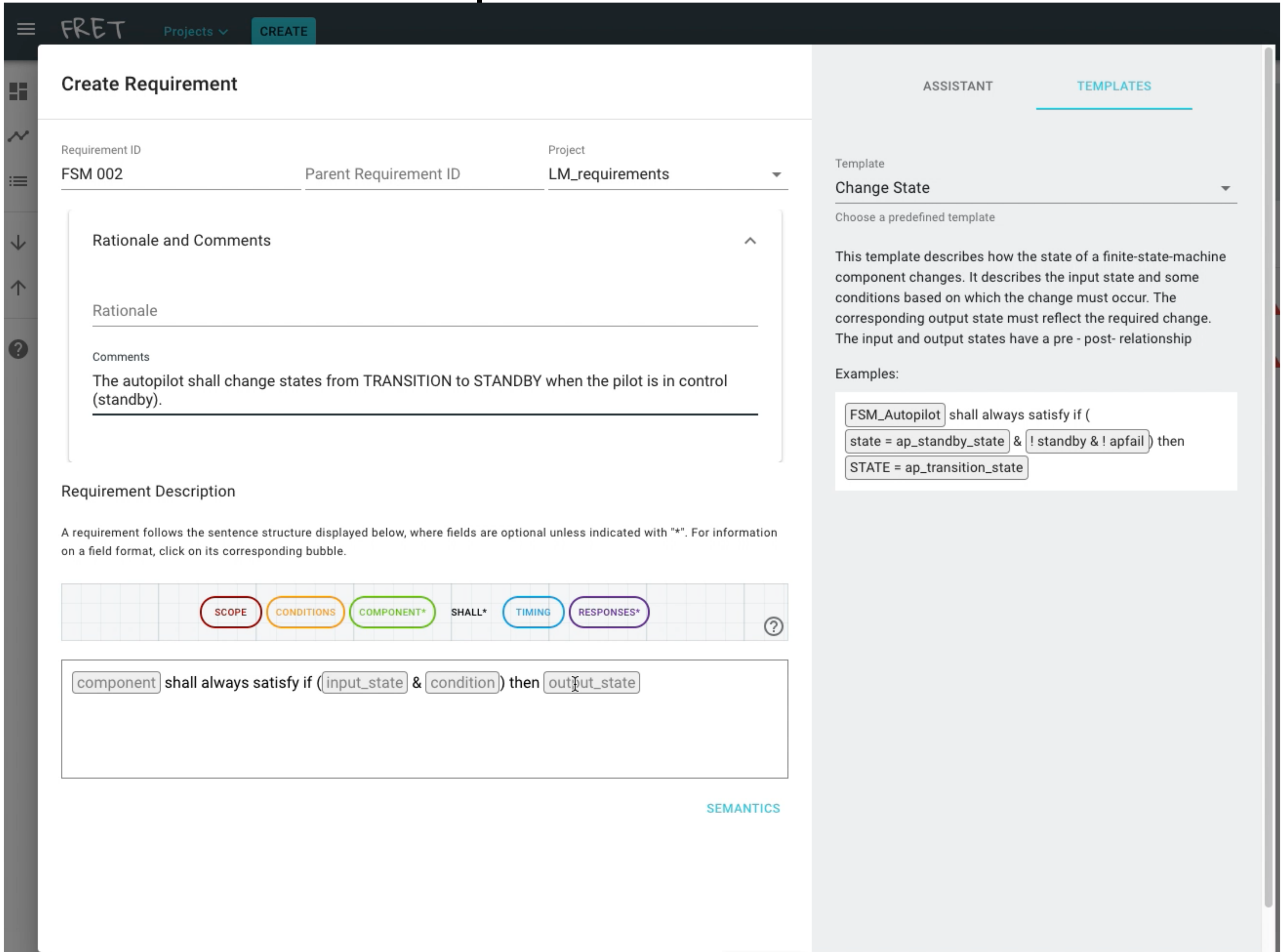

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Checking Consistency

Lockheed Martin Cyber-Physical System Challenge, component FSM:

Definition of a *Realizable* set of requirements: A system exists that satisfies the requirements for *every* valid environment input.

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Checking Realizability

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Input state: TRANSITION

Checking Realizability

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Input state: TRANSITION ✓
Condition 1: pilot is in control ✓
Condition 2: system is supported ✓
sensor data is good ✓

Checking Realizability

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Input state: TRANSITION ✓
Condition 1: pilot is in control ✓
Condition 2: system is supported ✓
sensor data is good ✓
Output state 1: STANDBY
Output state 2: NOMINAL

The system must be consistent for any valid environmental input.

Checking Realizability

- Realizable requirements: A system exists that satisfies the requirements for *every* valid environment input
- Unrealizable requirements: Diagnostic analysis
  - Identify minimal sets of unrealizable requirements in specification
  - Counterexamples
  - Simulation of conflicting requirements
- Compositional Realizability Checking
  - *Connected Components (CC)*: sets of requirements where the sets can be analyzed independently

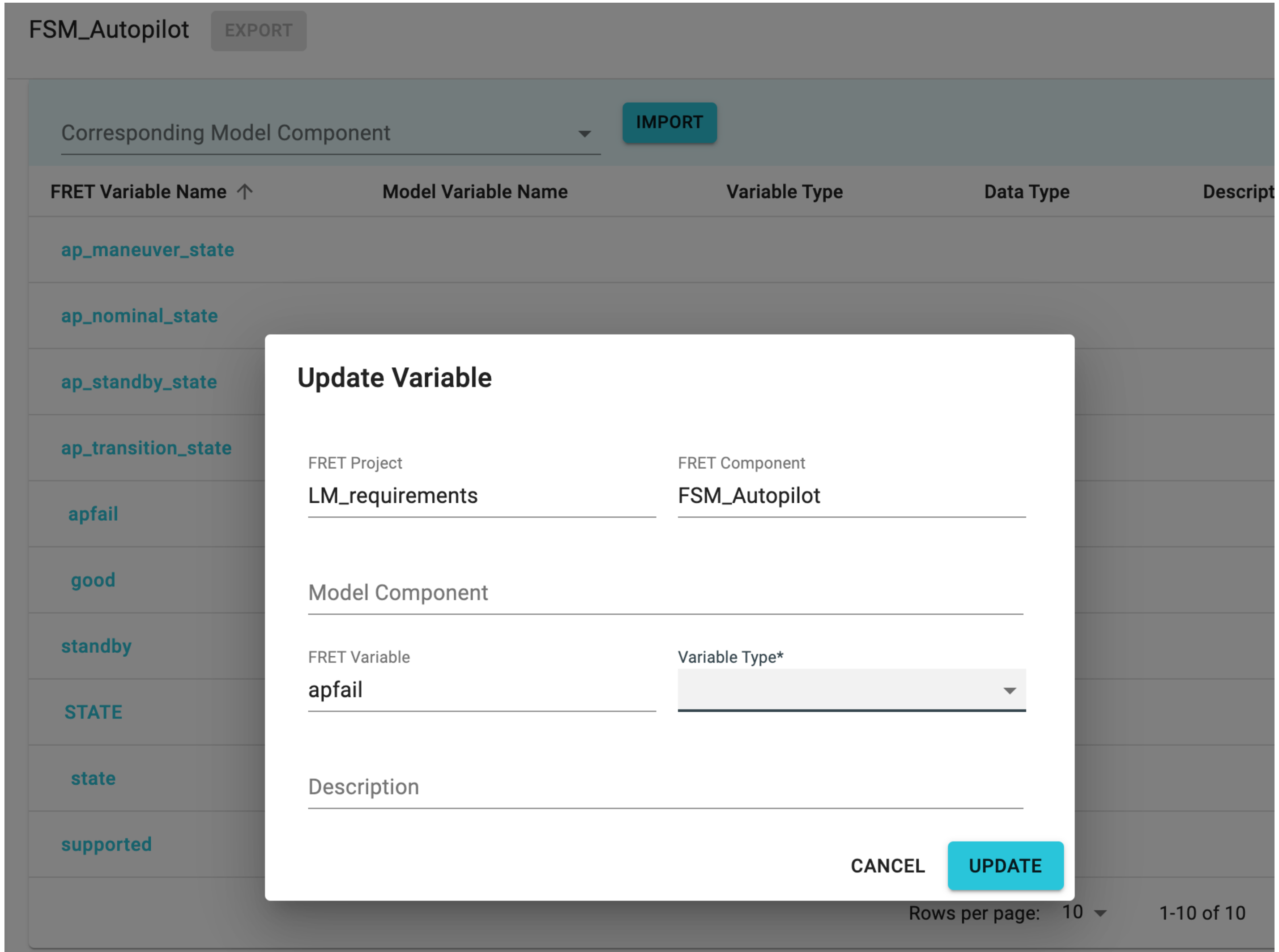
Giannakopoulou, Dimitra, Andreas Katis, Anastasia Mavridou, and Thomas Pressburger. "Compositional realizability checking within FRET." (NASA/TM–20210013008).

Mavridou, Anastasia, Andreas Katis, Dimitra Giannakopoulou, David Kooi, Thomas Pressburger, and Michael W. Whalen. "From Partial to Global Assume-Guarantee Contracts: Compositional Realizability Analysis in FRET." FM 2021

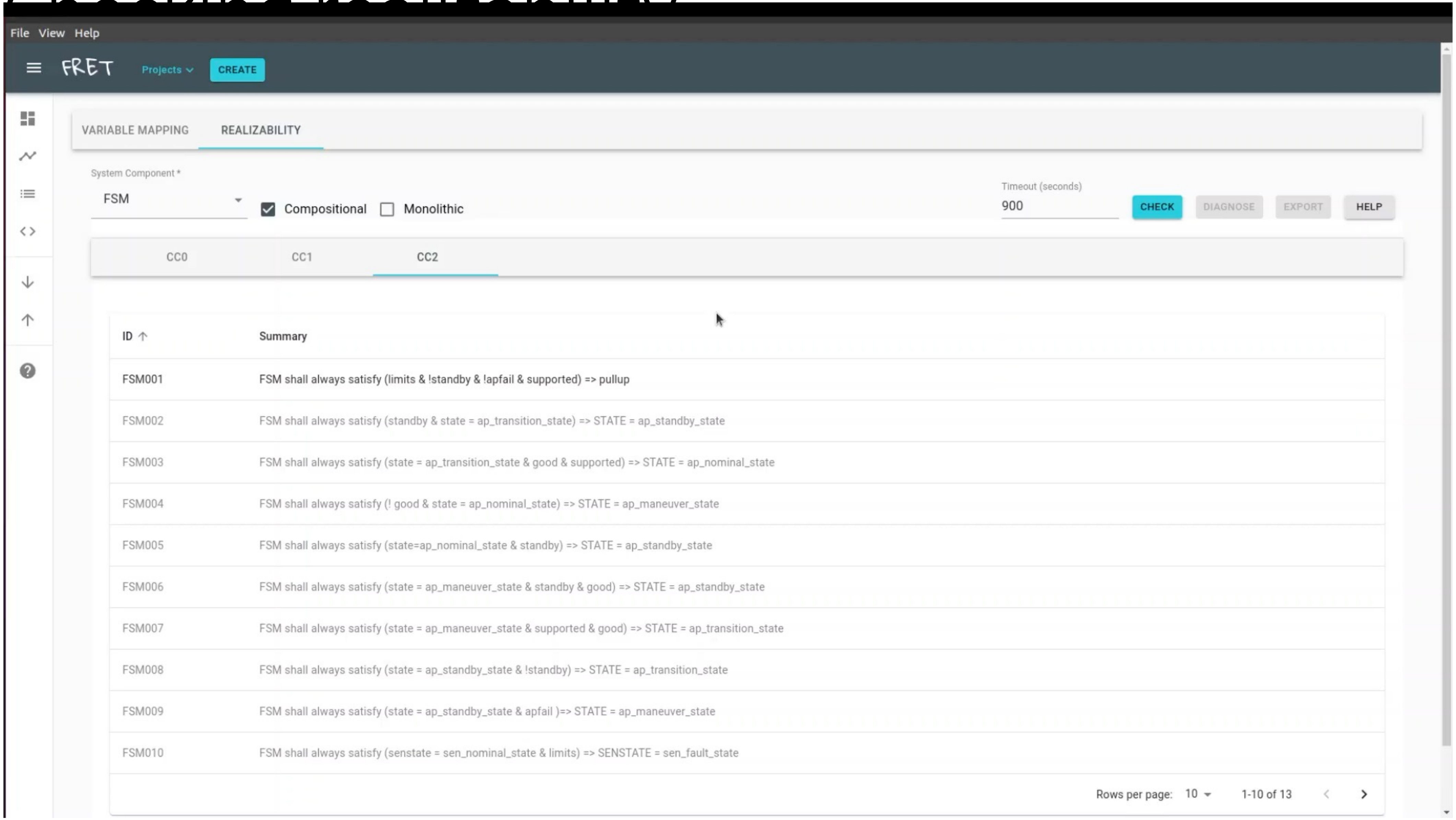
Variable declaration

- Variable name in requirement
- Variable Type:
  - Input (the system monitors the variable)
  - Output (the system controls the variable)
  - Internal: just a name for a Lustre expression, like a macro.
- Datatype
  - Boolean, integer, double, unsigned integer, single

Variable Declaration/Mapping Dialog



Checking realizability



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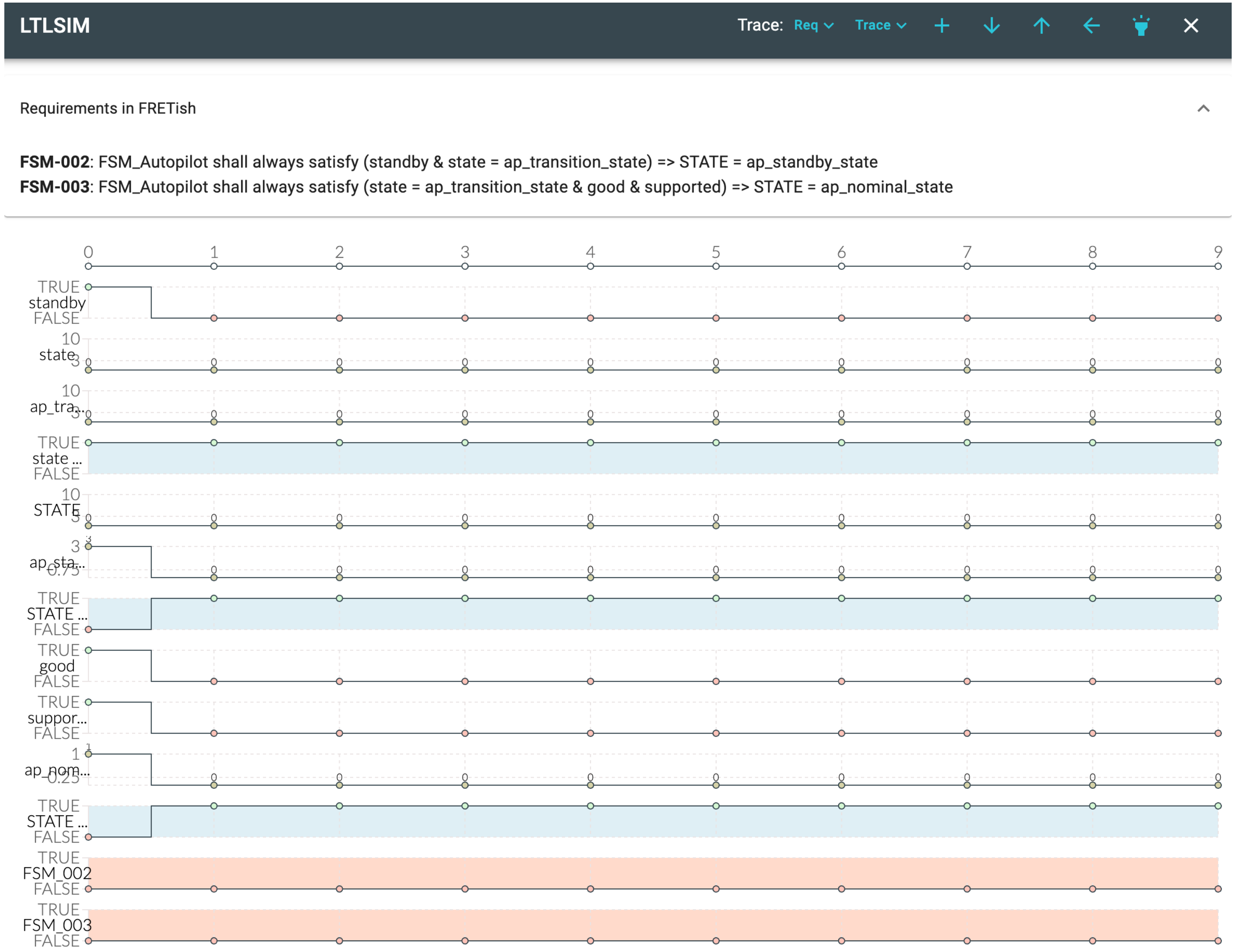
Simulation of Counterexample



FRET bridges the gap

- Captures requirements in a restricted natural language with unambiguous semantics
- Explains formal semantics in various forms: natural language, diagrams, interactive simulation
- Assists in writing requirements through requirement templates
- Formalizes requirements in a compositional (hence maintainable and extensible) manner
- Checks consistency of requirements and provides feedback

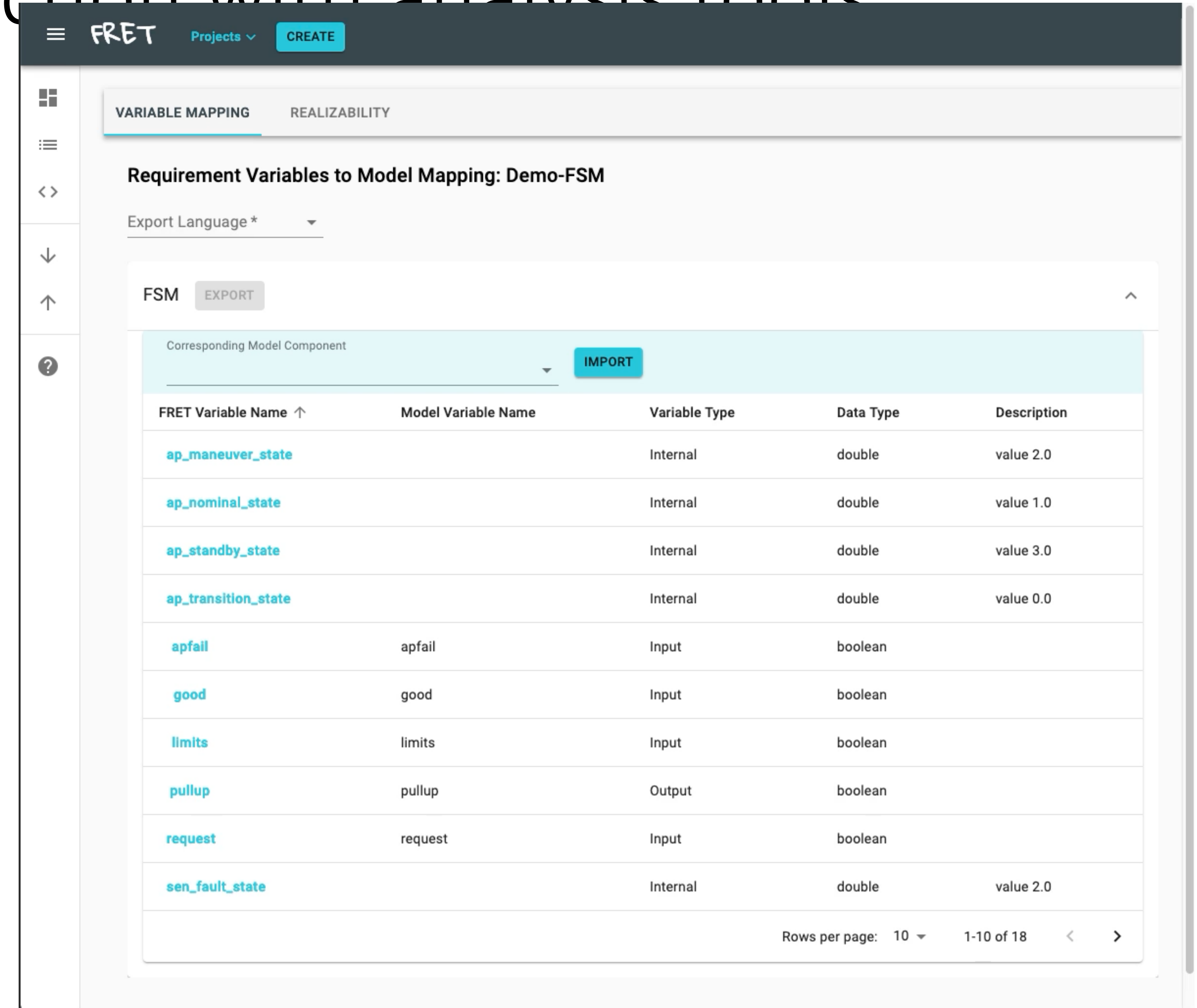
Connects with analysis tools and exports verification code

- ✓ for model checking Simulink models with CoCoSim
- ✓ for model checking Lustre code with Kind2
- ✓ for efficient runtime monitoring with Copilot

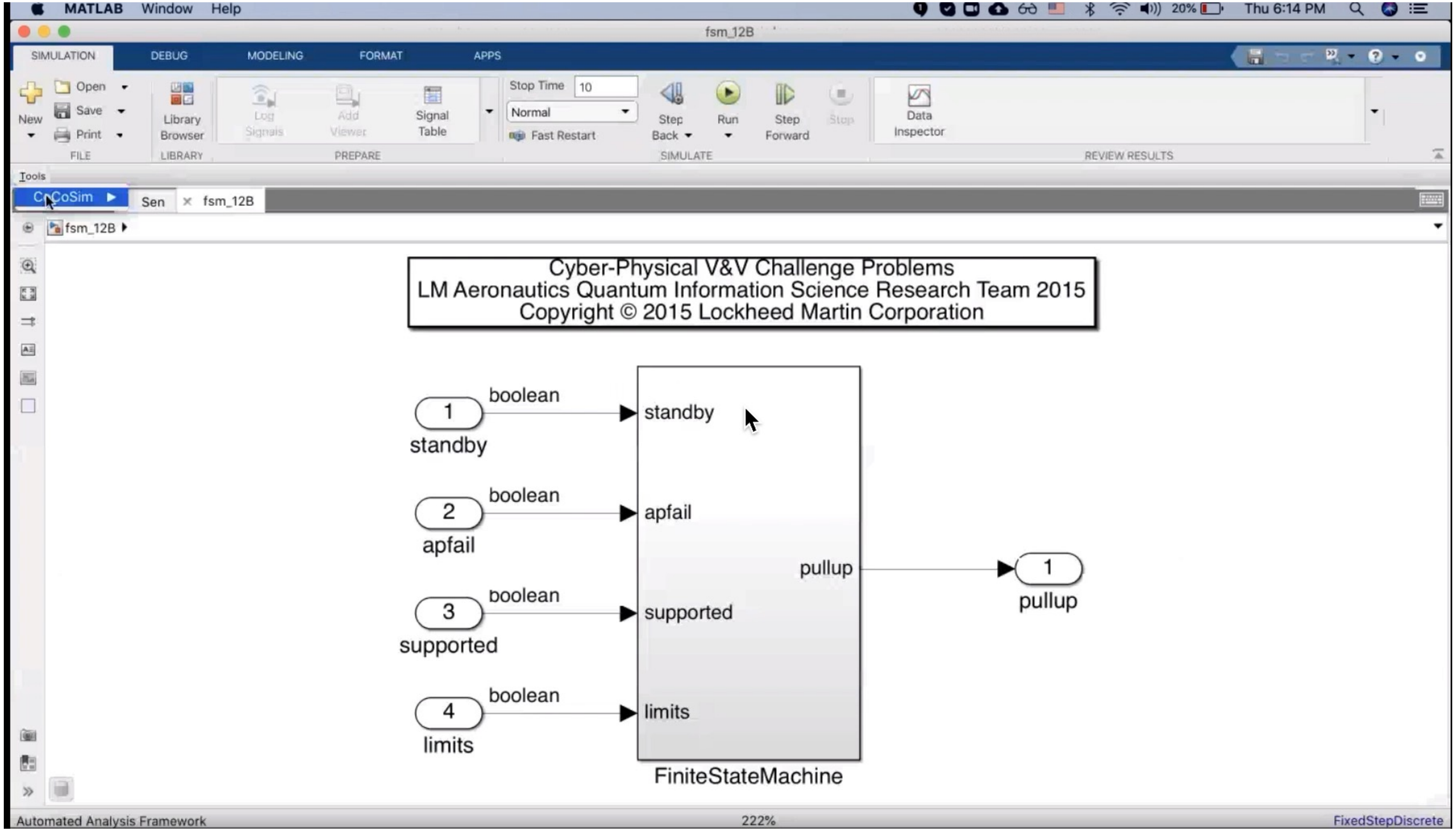
Variable mapping

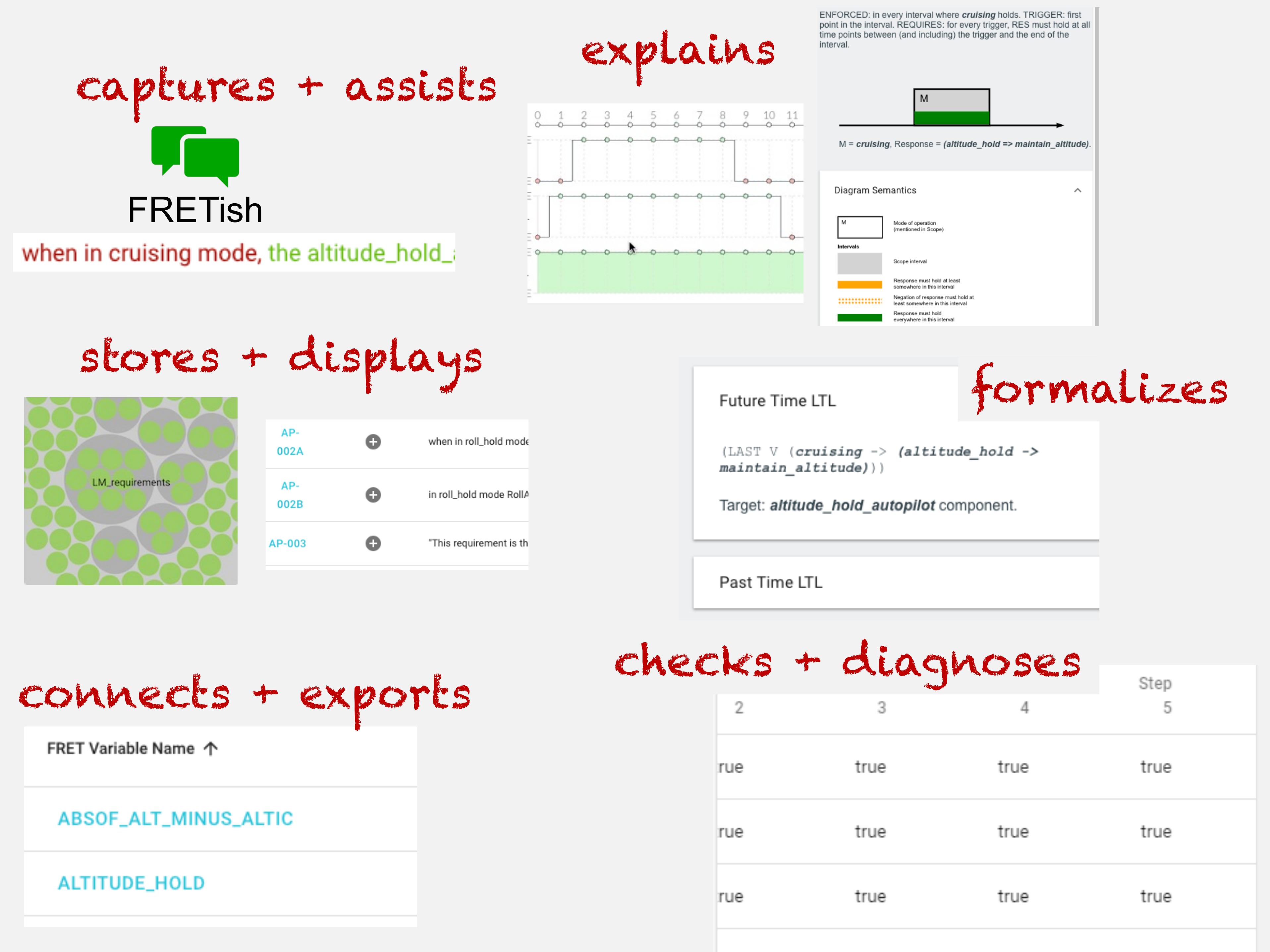
- In target model/code: e.g., the corresponding signal in Simulink model
  - Simulink architectural information can be imported into FRET so user can navigate/choose among possibilities

Connection with analysis tools



Connection with analysis tools




captures + assists
FRETish
when in cruising mode, the altitude_hold_
explains
ENFORCED: in every interval where cruising holds. TRIGGER: first point in the interval. REQUIRES: for every trigger, RES must hold at all time points between (and including) the trigger and the end of the interval.
M
M = cruising, Response = (altitude_hold => maintain_altitude).
Diagram Semantics
Mode of operation (mentioned in Scope)
Intervals
Scope interval
Response must hold at least somewhere in this interval
Negation of response must hold at least somewhere in this interval
Response must hold everywhere in this interval
stores + displays
LM_requirements
AP-002A
when in roll_hold mode
AP-002B
in roll_hold mode RollA
AP-003
"This requirement is th
formalizes
Future Time LTL
(LAST V (cruising -> (altitude_hold -> maintain_altitude)))
Target: altitude_hold_autopilot component.
Past Time LTL
connects + exports
FRET Variable Name
ABSOF_ALT_MINUS_ALTIC
ALTITUDE_HOLD
checks + diagnoses
Step
2 3 4 5
rue true true true
rue true true true
rue true true true

Ready for FRETish?

FRET's mission is to provide an intuitive platform for capturing precise requirements, to serve as a portal to a variety of analysis tools, and to support requirements repair based on analysis feedback.

https://github.com/NASA-SW-VnV/fret

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Thank you