Formal Analysis of a **Triplex Sensor Voter** at Rockwell Collins France

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Perpignan

Agenda

1) Presentation Rockwell Collins

2) The Rockwell Collins Translator Framework

3) Analysis of a Triplex Sensor Voter

Rockwell Collins France

- Rockwell Collins France (RCF) is an **electronic systems manufacturer**
- 700+ employees, mainly located in Toulouse, France, subsidiary of Rockwell Collins Inc. (20.000 empl.)
- Systems and equipments for aircraft and rotary wing manufacturers (Airbus, Eurocopter, Augusta,…)
  - Communication, Navigation, Radar, Surveillance, Cockpit equipments
- We provide communication systems for European MODs (radio, networks)
  - Software define radio, Data Links (Link11, Link 16,…), Localization and SAR (Search And Rescue) equipments

Formal Methods at Rockwell Collins

- In the US: team of ~10 research engineers (mostly PhD)
- Work on
  - model checking (MATLAB Simulink© **translator framework**)
  - Theorem proving (especially **ACL2**)
- For 1,5 years, 1 research engineer in France
- Starting in october 2010, a PhD in France (CIFRE with ONERA)

The Rockwell Collins Translator Framework

- Purpose : Verification of **SCADE™** and **MATLAB Simulink©** models

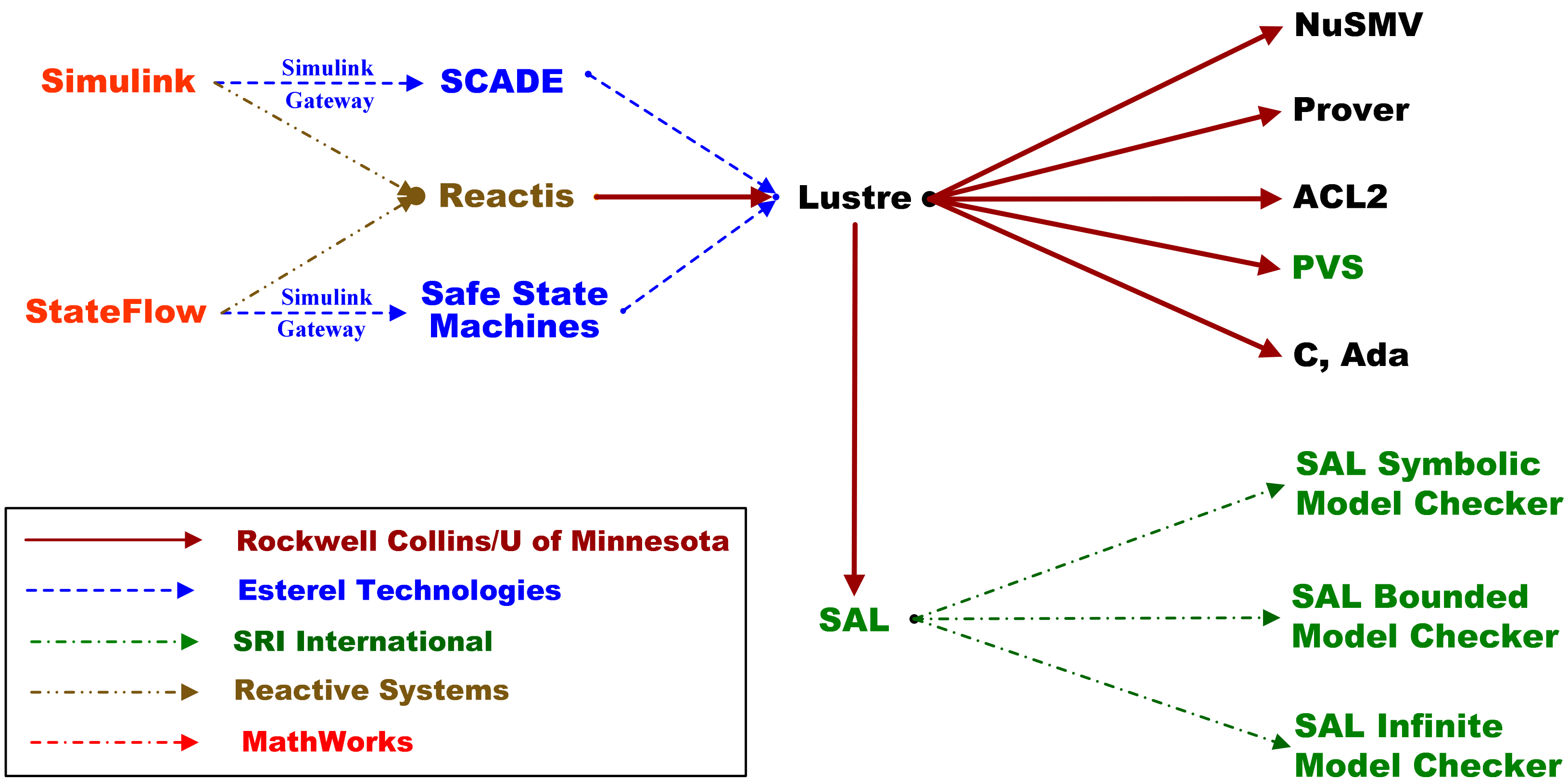
- **Long term effort** in the domain of formal methods

- Used on **several projects** (see articles by Steven Miller and Michael Whalen, e.g. *Software model checking takes off,* CACM 53(2), 2010)

- Based on an extension of **Lustre** as intermediate language

- Can output **optimized descriptions** in input languages of several **different analyzers**

The Rockwell Collins Translator Framework (2)



The Triplex Sensor Voter

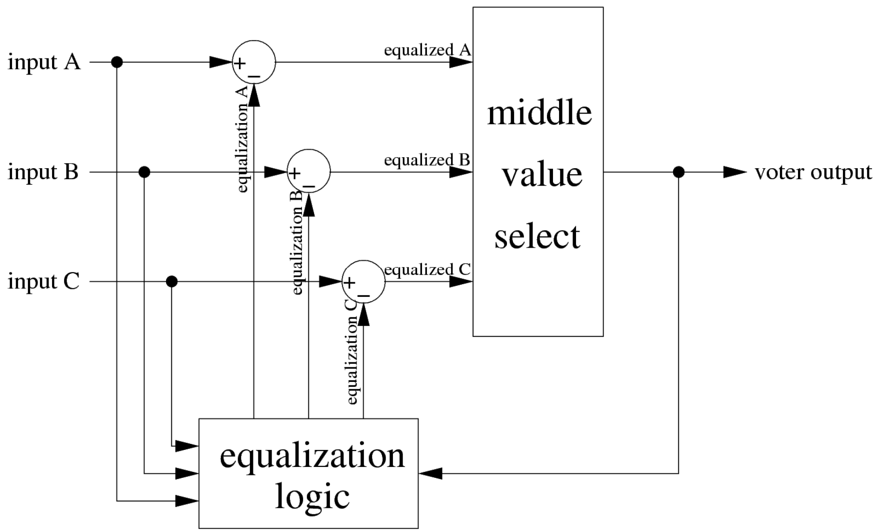
- Compute an output from input of **three redundant sensors**
- Able to detect and eliminate one **faulty sensor**
- User **reset** possible
- Implemented in **Simulink**
- Several blocks:
  - Value computation (arithmetic)
  - Fault detection (mainly boolean)
  - Reset (purely boolean)

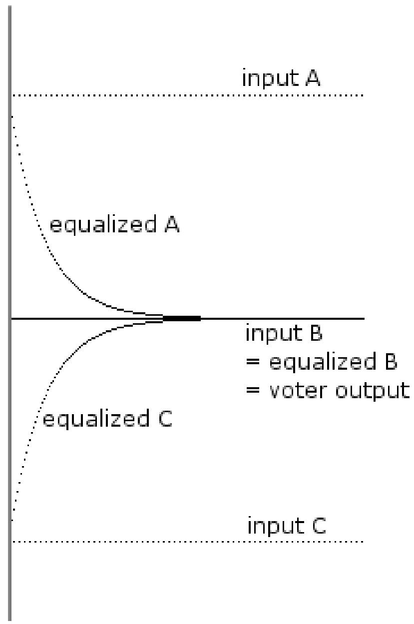
Industrial Context of the Analysis

- **Legacy** model (~20 years old)
- Reverse engineering – **why** and **how** does it work ?
- Finding right **parameters** is **very time consuming**
- Has been **qualified**, high confidence
- **Modifications** are made now
  - Better usage of Simulink
  - 4th input ?
- **New application** areas

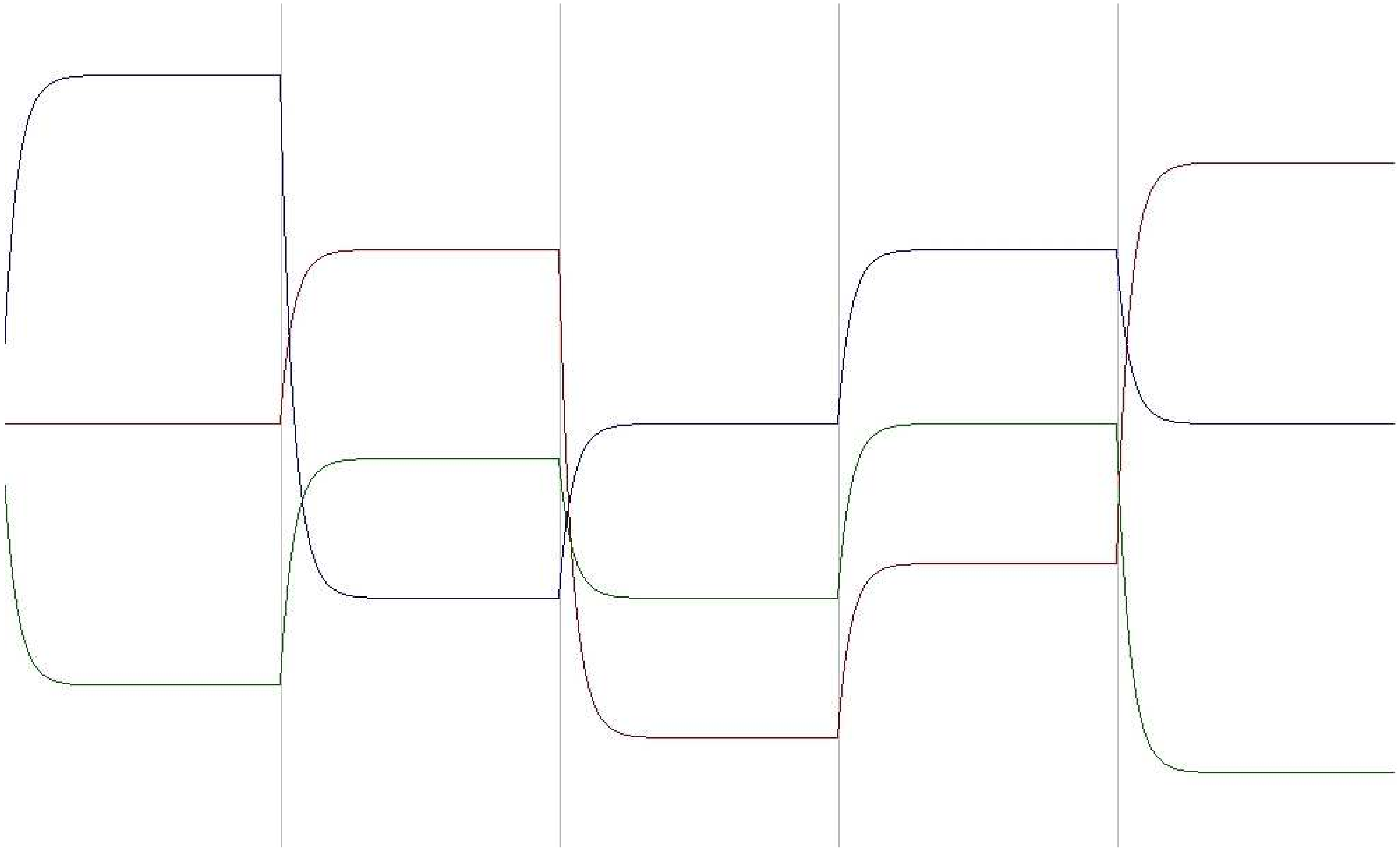
Normal Operation Mode of the Voter (no fault)

- From each of the three inputs, subtract an equalization value
- Output is middle value of equalized values
- Equalization based on integration – 3 memories of rational type

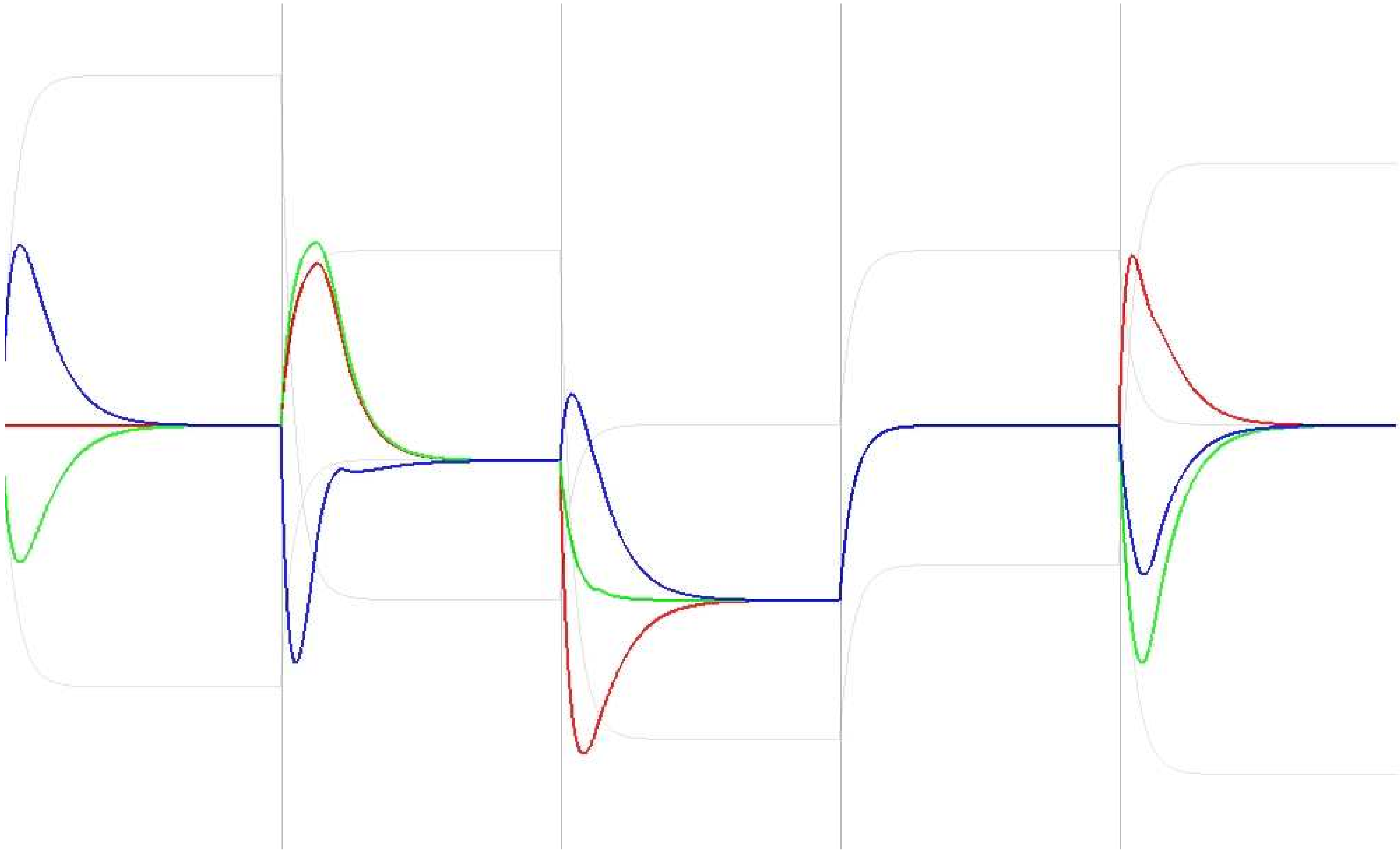




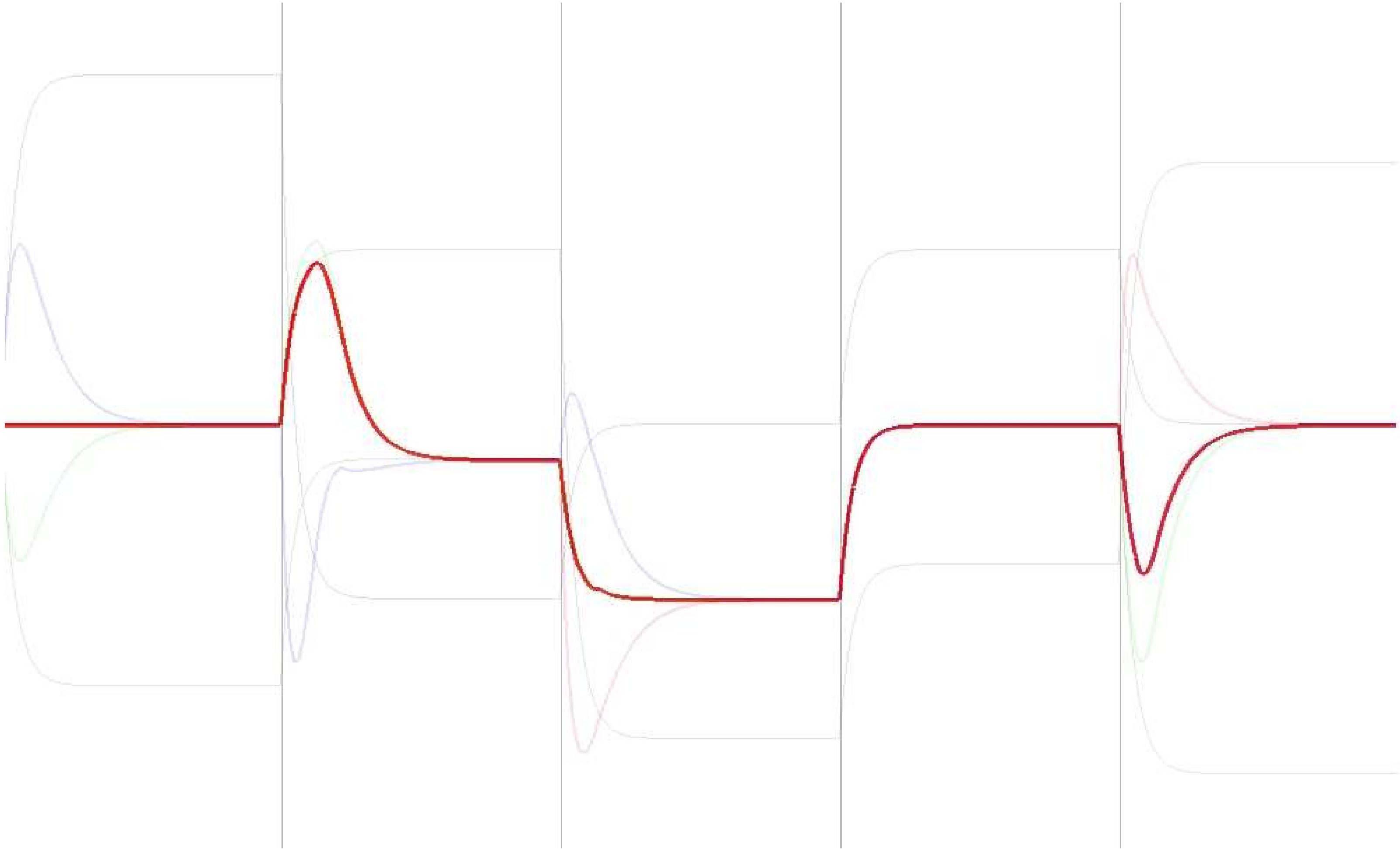
Simulation: Input Values



Simulation: Equalized Values



Simulation: Output Value



Equations of the Normal Operation Mode

$$EqualizationA_0 = 0.0$$
$$EqualizationB_0 = 0.0$$
$$EqualizationC_0 = 0.0$$

$$Centering_t = middleValue(EqualizationA_t, EqualizationB_t, EqualizationC_t)$$

$$EqualizedA_t = InputA_t - EqualizationA_t$$
$$EqualizedB_t = InputB_t - EqualizationB_t$$
$$EqualizedC_t = InputC_t - EqualizationC_t$$

$$VoterOutput_t = middleValue(EqualizedA_t, EqualizedB_t, EqualizedC_t)$$

$$EqualizationA_{t+1} = EqualizationA_t + 0.05 * (sat_{0.5}(EqualizedA_t - VoterOutput_t) - sat_{0.25}(Centering_t))$$
$$EqualizationB_{t+1} = EqualizationB_t + 0.05 * (sat_{0.5}(EqualizedB_t - VoterOutput_t) - sat_{0.25}(Centering_t))$$
$$EqualizationC_{t+1} = EqualizationC_t + 0.05 * (sat_{0.5}(EqualizedC_t - VoterOutput_t) - sat_{0.25}(Centering_t))$$

Sensors and their Faults

- Non-faulty sensors furnish a value within an interval around true value determined by constant **MaxSensorError**

  abs(SensorValue – TrueValue) $\leq$ MaxSensorError

- Fault detection is based on **equalization** values

Objectives of the Analysis

- Analyse output to show that **transient peaks** cannot occur
- Find good **parameters** for fault detection and prove that a non-faulty sensor is never eliminated
- **Correct behaviour** : output tends to middle input value
- No **overflows**
- In general, what can we do with our **translator framework** ?

Approach of the Analysis

- Check on **model level**
- Handle **real** values in model as **rational** values
- Proof by induction -> **invariants** necessary

Example Properties

- What is the **maximal output error** for a given maximal sensor error ?

$$abs(VoterOutput - TrueValue) \leq ?$$

- What is the **maximal difference** of two equalization values for a given maximal sensor error ?

$$abs(EqualizationA - EqualizationB) \leq ?$$

Inductive Invariant

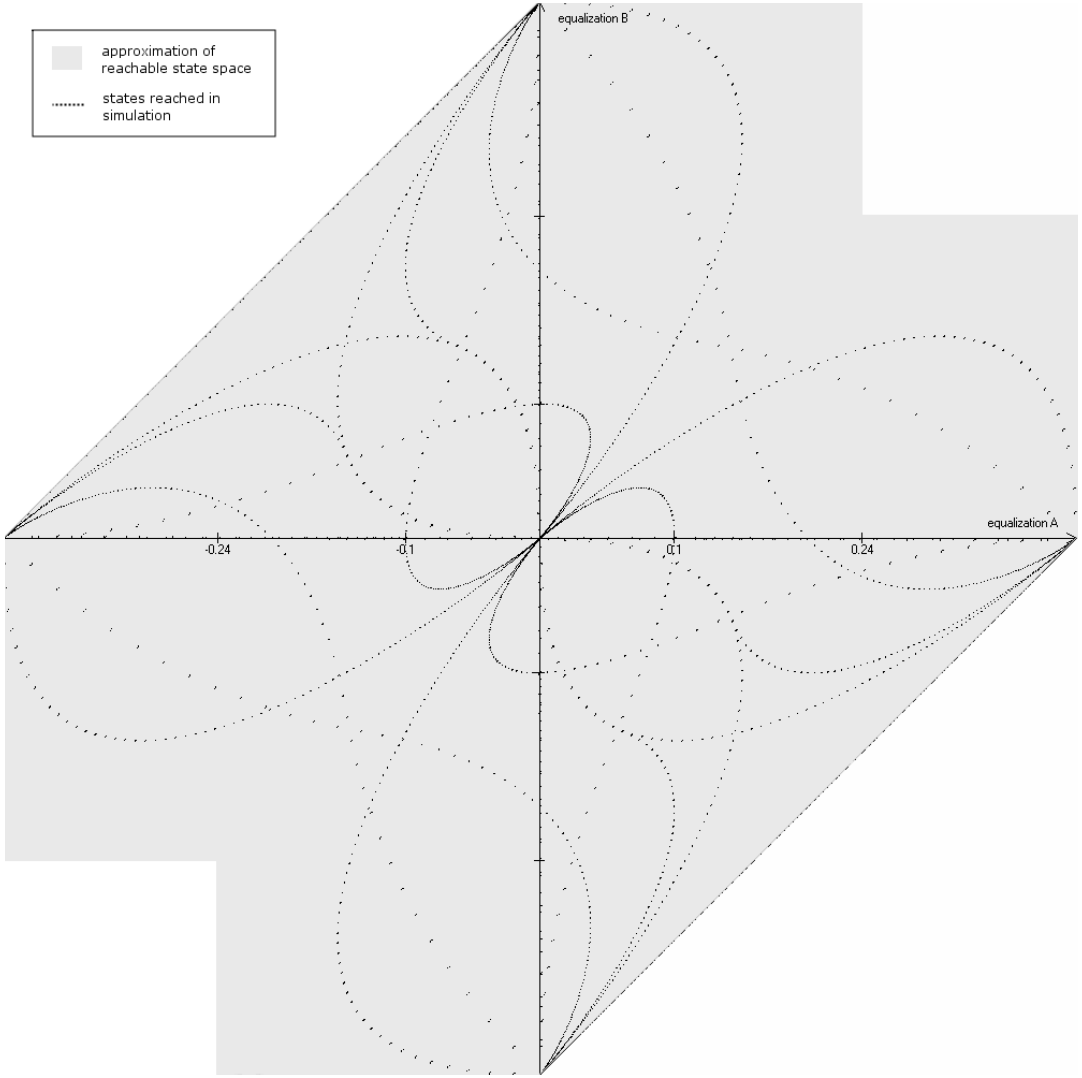
- Abs(EqualizationA - EqualizationB) <= 0.4
- Abs(EqualizationA - EqualizationC) <= 0.4
- Abs(EqualizationB - EqualizationC) <= 0.4

- Abs(EqualizationA + EqualizationB + EqualizationC) <= 0.66

- Abs(EqualizationA) <= 0.4
- Abs(EqualizationB) <= 0.4
- Abs(EqualizationC) <= 0.4

- Abs(middle(EqualizationA,EqualizationB, EqualizationC)) <= 0.24

Simulation and Proof



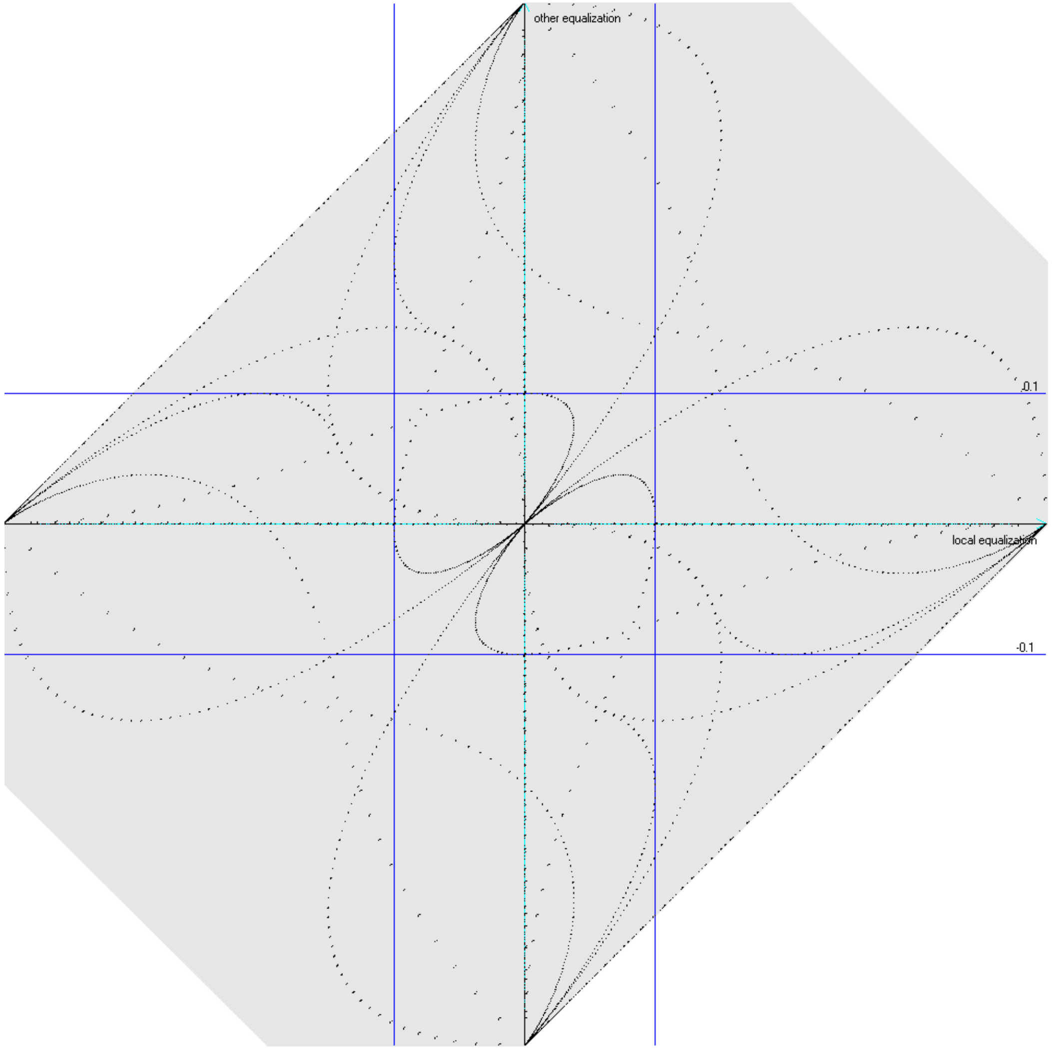
Inductive Octagonal Invariant

- Abs(EqualizationA) <= 0.4
- Abs(EqualizationB) <= 0.4
- Abs(EqualizationC) <= 0.4

- Abs(EqualizationA - EqualizationB) <= 0.4
- Abs(EqualizationA - EqualizationC) <= 0.4
- Abs(EqualizationB - EqualizationC) <= 0.4

- Abs(EqualizationA + EqualizationB) <= 0.6
- Abs(EqualizationA + EqualizationC) <= 0.6
- Abs(EqualizationB + EqualizationC) <= 0.6

Inductive Octagonal Invariant



Simple Automatic Generation of Inductive Invariants

Choose a set of expressions $\mathbf{expr_1}$, …, $\mathbf{expr_n}$ over state variables

```
v1, …, vn = 0.0

Repeat
    Check if (abs(expr1)<=v1 and … and abs(exprn)<=vn)
                is inductive invariant
    For all i
        If step counter example exists with abs(expri)>vi
            vi += 0.01
Until no counter example exists
```

Analysis with Astrée

- Implementation of the (reduced) voter in C
- Astrée casts **false alarms** on **overflow** of equalization values
- Communicated to AbsInt
- Confirm the inductive invariant on code level ?

Lessons Learnt from Analysis

- Inductive proof was used, finding invariants was very **time consuming**
- All terms in invariant are **linear** (sums and differences)
- For max output error : still **gap** between value found by simulation and value proved
- **BMC not helpful** : too many steps necessary

Ongoing Work

- Extension to **fault case**
- **Speed up analysis** by adding lemmas
- Try to find **closer approximation** of state space
- Experiment **different proof engines** (e.g. new version of Kind)

Future Directions

- Can invariants be found **automatically** ? By abstract interpretation ?
- **Other forms** of invariants (non-linear, combined with boolean conditions, etc.) ?
- Potential case study for **combining** model checking and abstract interpretation (CMACS, PhD RCF/ONERA)
- Relevance for implementation with **floating point numbers** ?

Thank you !