Model Checking of Aerospace Domain Models in an Industrial Context

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Rockwell Collins

Agenda

1. Presentation of Rockwell Collins
2. The RC formal analysis framework
3. Case studies
   - Adaptive Display & Guidance System
   - UAV Flight Control System
   - Effector Blender
   - Triplex Sensor Voter

} US

France

Presentation

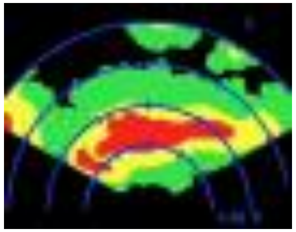
ROCKWELL COLLINS

Who Are We?

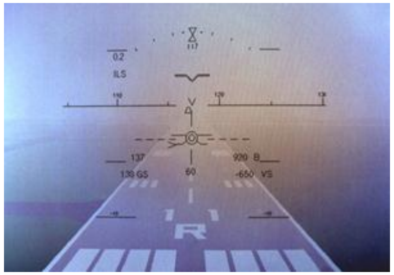
A World Leader In Aviation Electronics And Airborne/ Mobile Communications Systems For Commercial And Military Applications



- Communications
- Navigation



- Automated Flight Control
- Displays / Surveillance

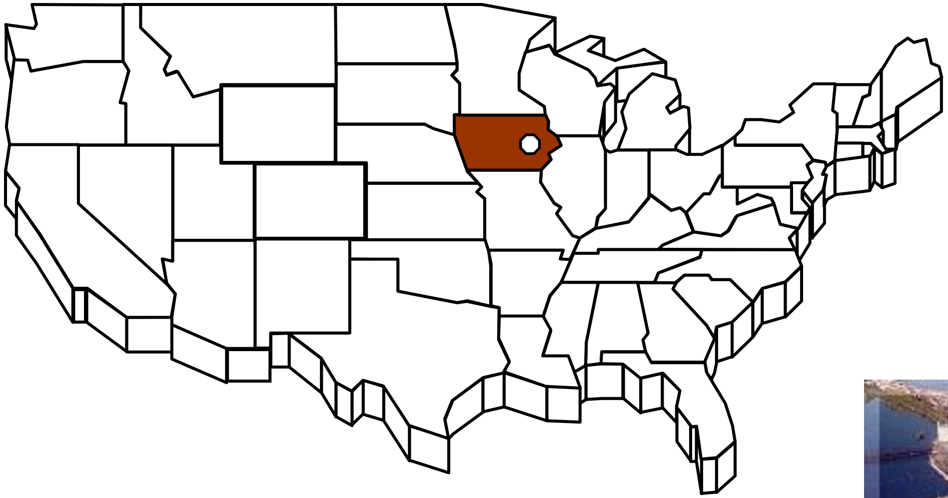



- Aviation Services

- In-Flight Entertainment
- Integrated Aviation Electronics
- Information Management Systems

Rockwell Collins

Headquartered in Cedar Rapids, Iowa
~20.000 Employees Worldwide
Present in 27 countries



Rockwell Collins France

- 700+ employees, mainly located in Toulouse, France
- R&D, development of own products and technologies (direction finder, …)
- 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

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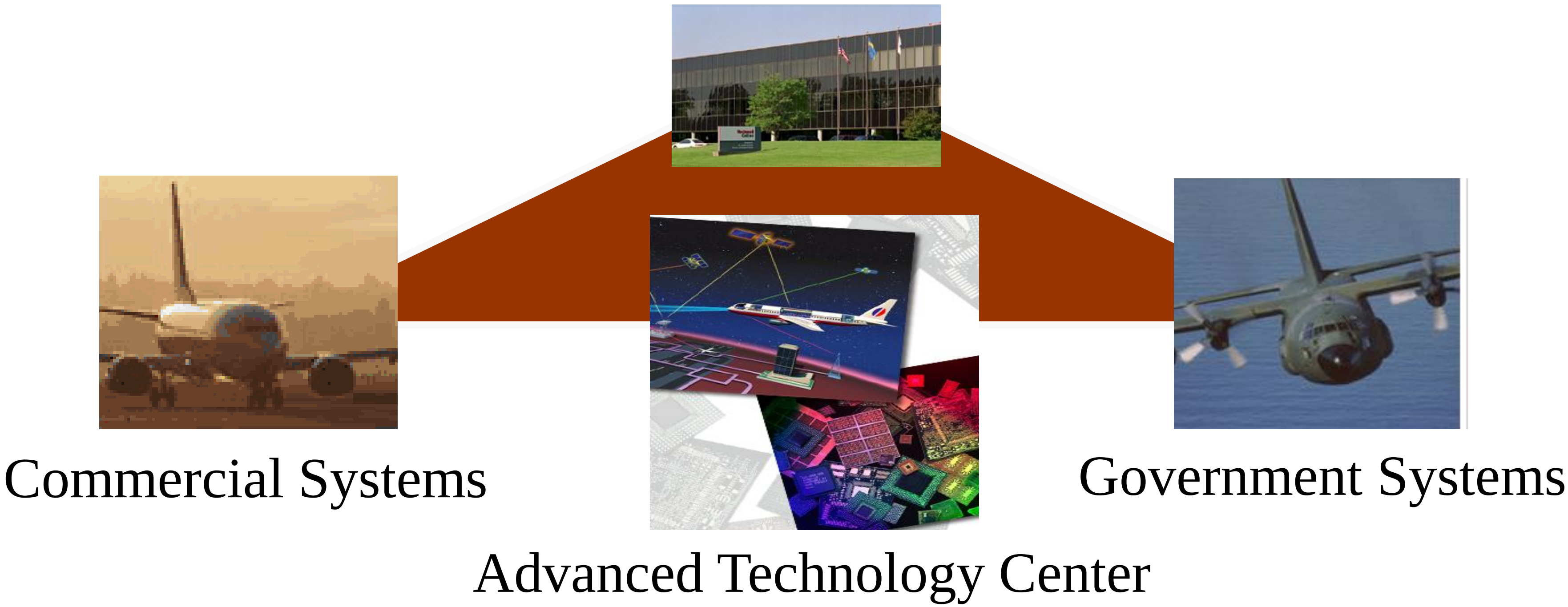
RCI Advanced Technology Center



- **The Advanced Technology Center (ATC) identifies, acquires, develops and transitions value-driven technologies**

- **The Automated Analysis section of ATC applies mathematical tools and reasoning**

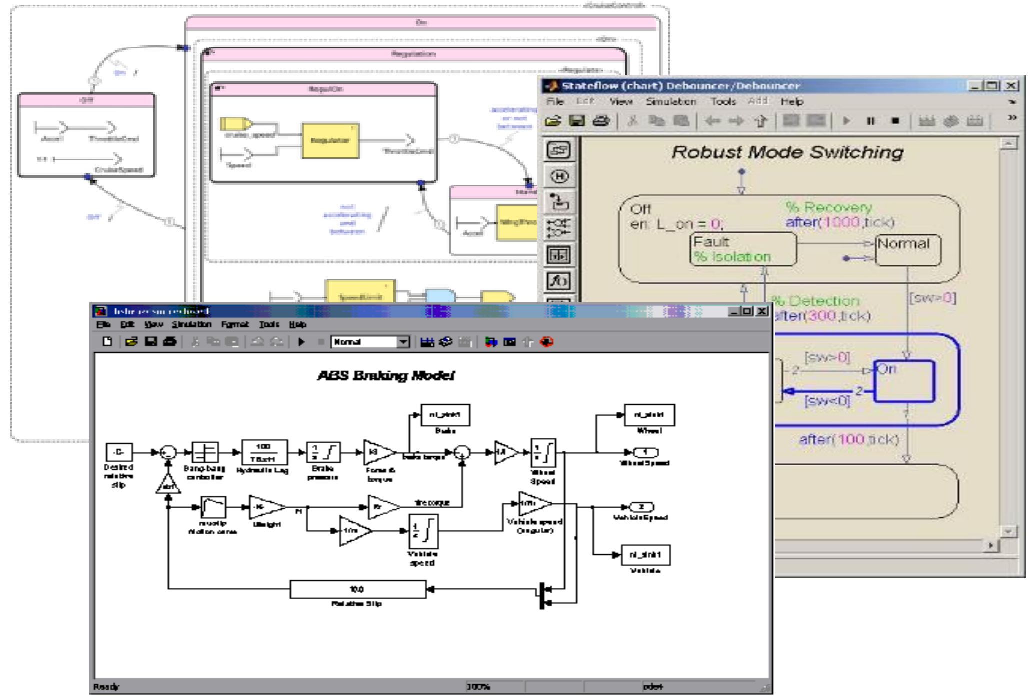
FM at Rockwell Collins France

- Since March 2009, 1 research engineer in Toulouse
- 2011 to 2013: PhD student – Combination of different techniques (model checking, abstract interpretation, …)
- Objectives:
  - Extension of the Automated Analysis section in the US
  - Participate in French and European Research Projects
  - Collaboration with industrial partners and customers and share experiences with them
  - Contact with European Research Institutions
  - Evaluation of tools (especially open source)

Activities in Model Checking

- Application in Model-Based Development
  - MATLAB Simulink®, Esterel Technologies SCADE Suite™
  - Enable early simulation and debugging
- Development of an in-house tool
  - Translator framework as front-end to different proof systems

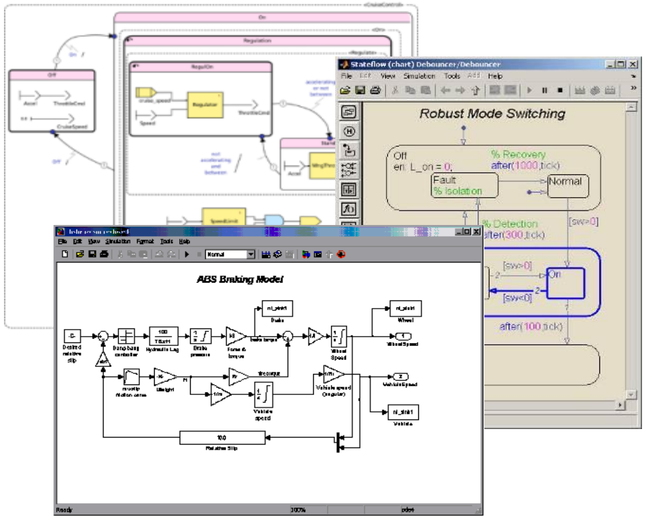
Reduce Costs and Improve Quality By Using Analysis to Find Errors During **Early** Design



In-House Tool

TRANSLATOR FRAMEWORK

Our In-House Tool:
The Rockwell Collins Translator Framework



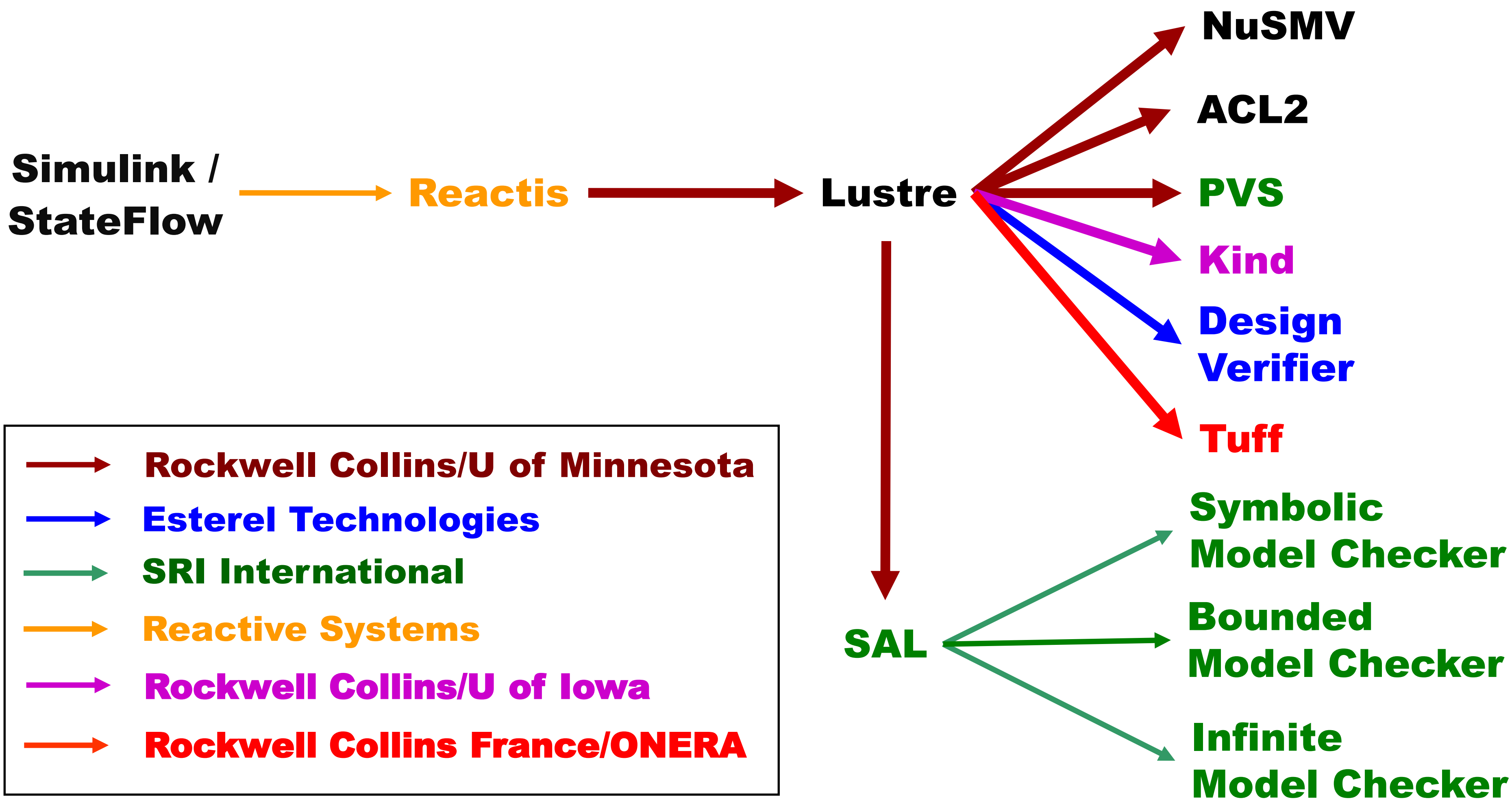
- Purpose : Formal Analysis of **SCADE™** and **MATLAB Simulink©** models

- **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)

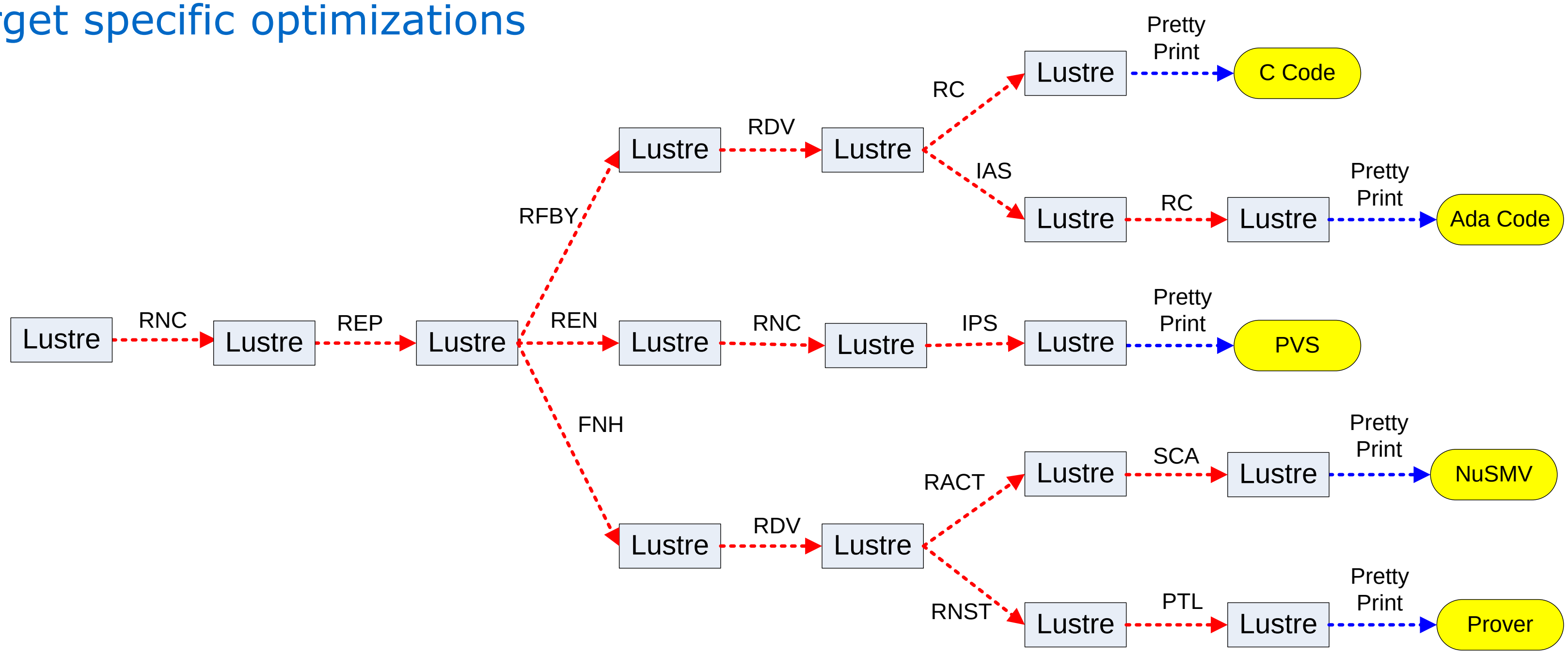
- Can output **optimized descriptions** in input languages of several **different analyzers**

The Rockwell Collins Translator Framework



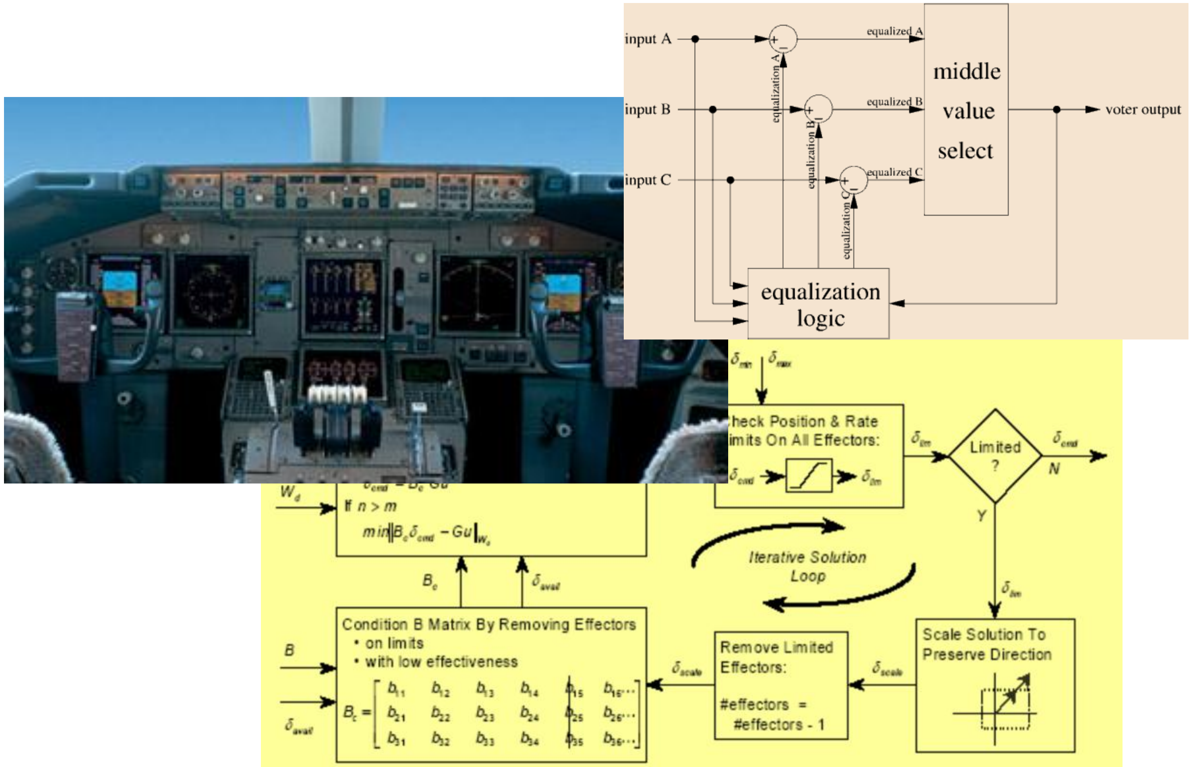
A Product Family of Translators

- Many small Lustre-to-Lustre translation passes
- Each pass refines closer to the target language
- Target specific optimizations



Translators Optimize for Specific Analysis Tools

Model	CPU Time (For NuSMV to Compute Reachable States)		Improvement
	Before	After	
Mode1	> 2 hours	11 sec	> 650x
Mode2	> 6 hours	169 sec	> 125x
Mode3	> 2 hours	14 sec	> 500x
Mode4	8 minutes	< 1 sec	480x
Arch	34 sec	< 1 sec	34x
WBS	29+ hours	1 sec	105,240x



Model Checking

CASE STUDIES

ADGS-2100 Adaptive Display & Guidance System

Modeled in Simulink

Translated to NuSMV

4,295 Subsystems

16,117 Simulink Blocks

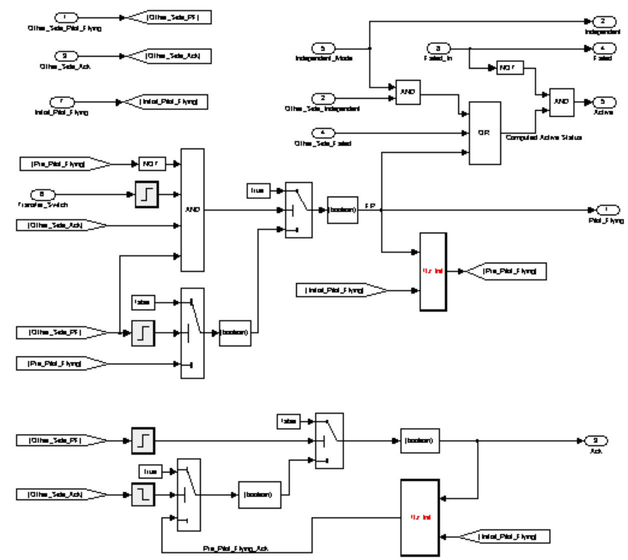
Over 10^{37} Reachable States

Example Requirement:

The Cursor Shall Never be Positioned on an Inactive Display

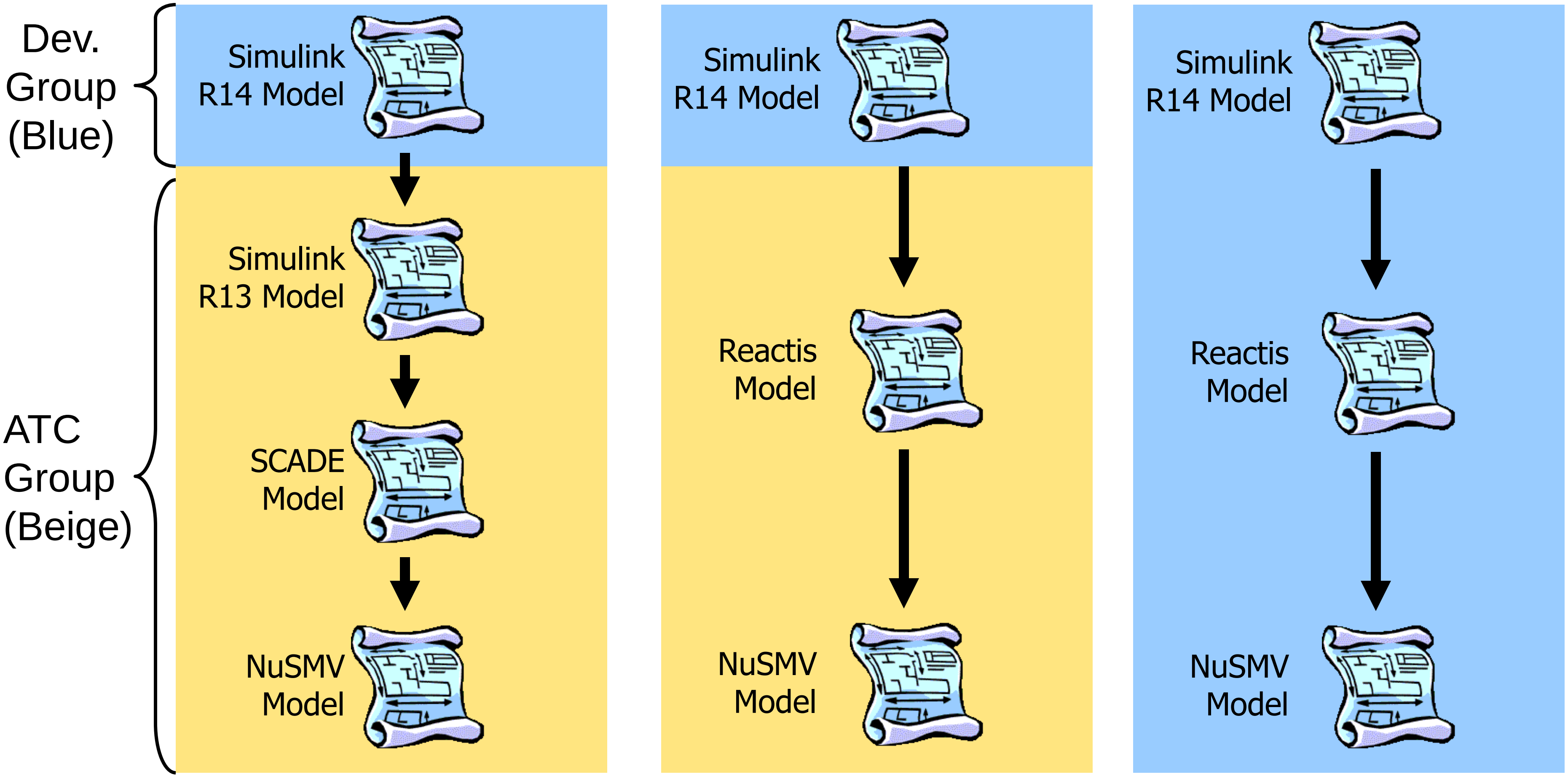
Counterexample Found in 5 Seconds

Checked 563 Properties - Found and Corrected 98 Errors in Early Design Models



ADGS-2100 Technology Transfer

Iteration 1 | Iteration 2 | Iteration 3



Iteration 1	Iteration 2	Iteration 3
Translation Time: 1-4 Hours	Translation Time: 10 Minutes	Translation Time: 10 Minutes
Turnaround: 1 Day to 1 Week	Turnaround: 3 Hours to 2 Days	Turnaround: 10 Minutes

Conclusion of this case study

Model Checking is successful in finding errors in early design models of our products

Case study for CerTA FCS Project (US)

- Sponsored by the Air Force Research Labs
- Can formal verification complement or replace some testing?
- Example Model – Lockheed Martin Adaptive UAV Flight Control System

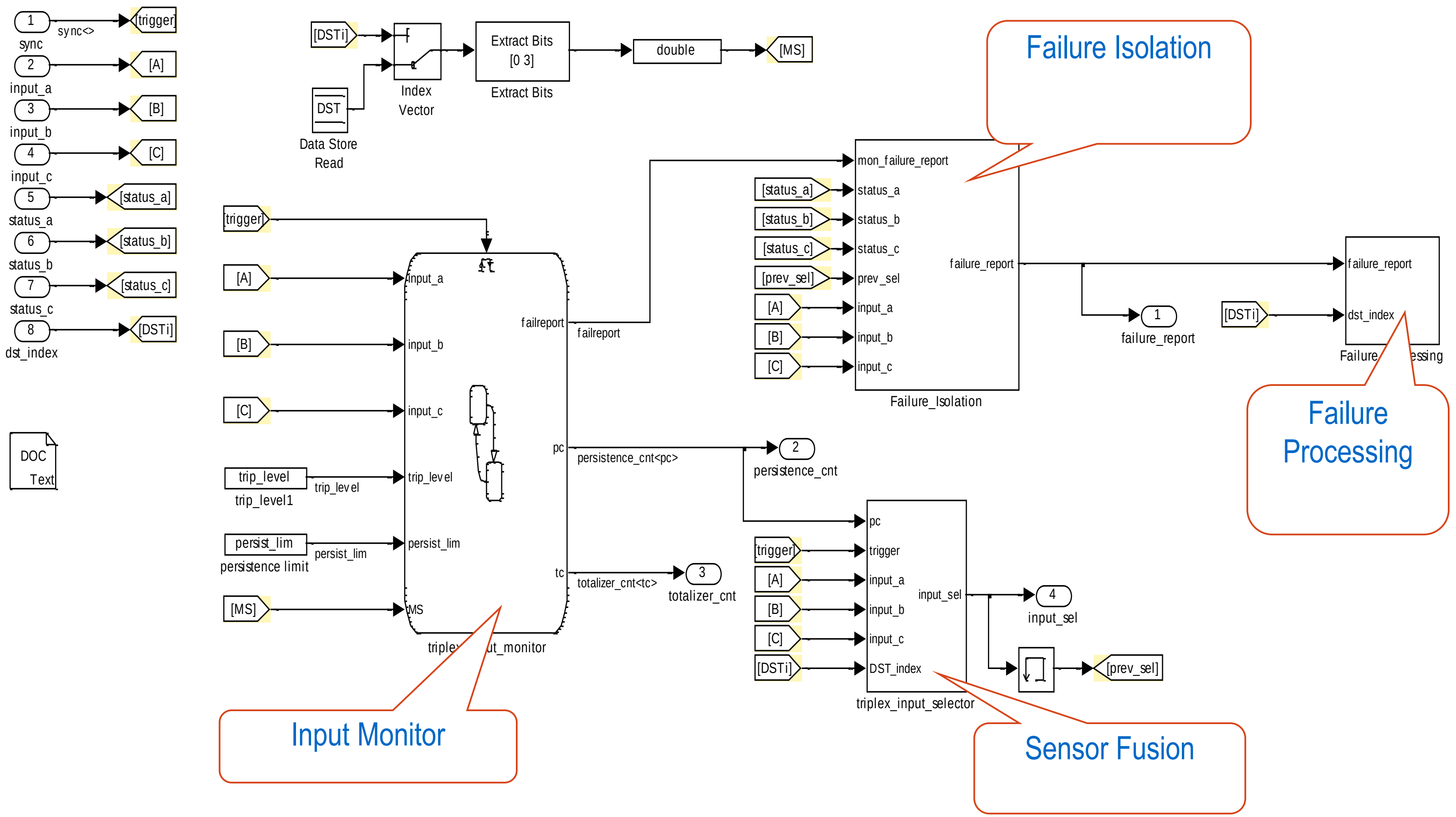
Lockheed Martin Aero

- Based on Testing
- Developed Tests from Requirements
- Executed Tests Cases on Test Rig

Rockwell Collins

- Based on Model-Checking
- Developed Properties from Requirements
- Proved Properties using Model-Checking

CerTA FCS Phase I - OFP Redundancy Management Logic



CerTA FCS Phase I – Errors Found

Errors Found in Redundancy Manager

	Model Checking	Testing
Triplex Voter	**5**	**0**
Failure Processing	**3**	**0**
Reset Manager	**4**	**0**
Total	**12**	**0**

- Model-Checking Found 12 Errors that Testing Missed
- Spent More Time on Testing than Model-Checking
  - 60% of total on testing vs. 40% on model-checking

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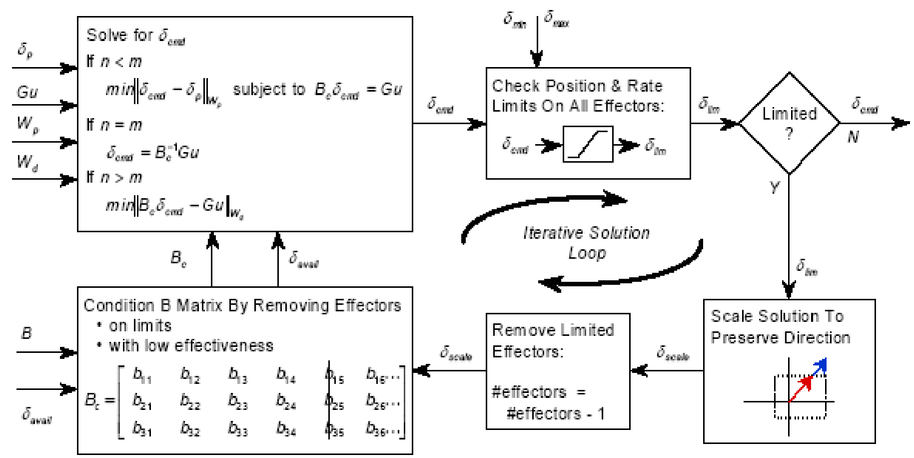
Conclusion of this case study

Model-checking was more
cost effective
than testing at finding errors
in design models of our products

Second use case for CerTA FCS Project (US)

- Sponsored by the Air Force Research Labs
- Can Model Checking be Used on Numerically Complex Systems?
- Example Model
  - Lockheed Martin Adaptive UAV Flight Control System
  - Generates actuator commands for aircraft control surfaces
  - Matrix arithmetic of real numbers



CerTA FCS Phase II – Verification of Floating Point Numbers

- Translate Floating Point Numbers into Fixed Point
  - Extended translation framework to automate this translation
  - Convert floating point to fixed point (scaling provided by user)

- Advantages & Issues
  - Use bit-level integer decision procedures for model checking
  - Results unsound due to loss of precision
  - Very valuable tool for debugging

CerTA FCS Phase II - Results

- Errors Found
  - Five previously unknown errors that would drive actuators past their limits
  - Several implementation errors were being masked by defensive programming

Conclusion of this case study

Model-Checking is useful for debugging numerically complex systems

Analysis of a Triplex Sensor Voter (RCF)

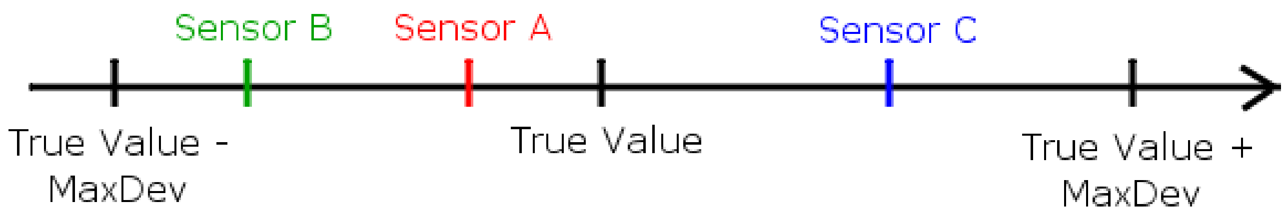
- Prove
  - Stability
  - Absence of runtime errors
  - Correct choice of parameters
- Analysis based on modern SMT solvers
- No abstraction of real numbers

Case Study : Triplex Sensor Voter

- Compute an output from input of **three redundant sensors**
- Modelled in **Simulink**
- Uses arithmetical operations on **real values**
- Includes low pass filtering, so has **internal state**

Sensor Characteristics

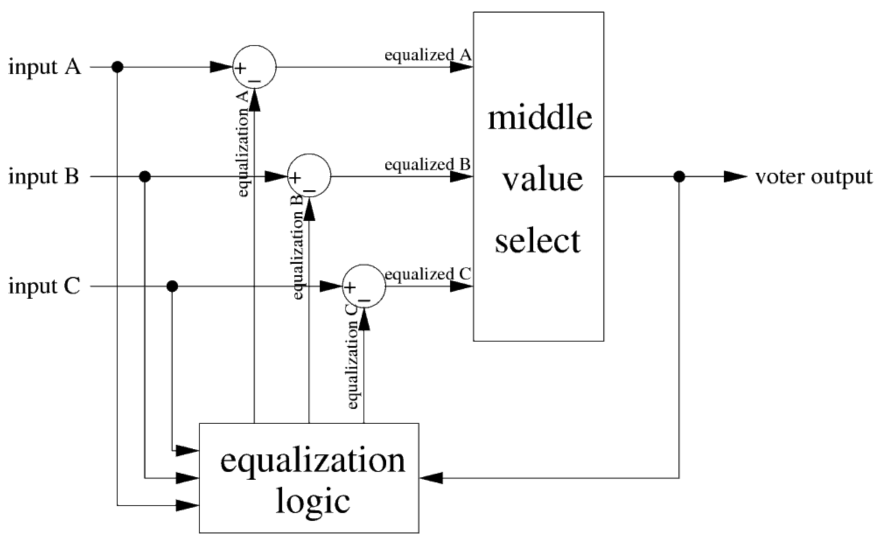
- Non-faulty sensors furnish a value within an interval around true value determined by a constant **MaxDev**

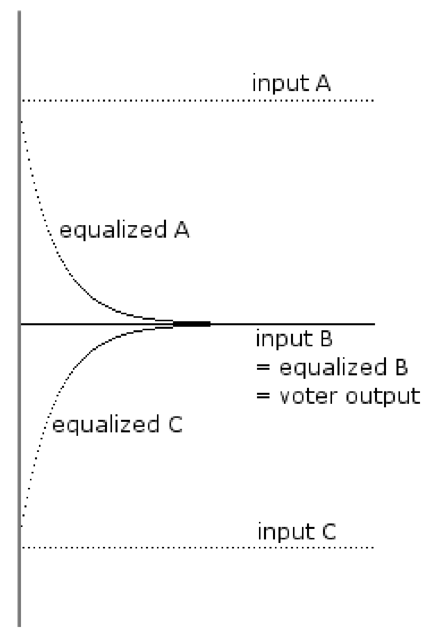


- In our analysis, we assume that sensors are **non-faulty**
- Result allows to paramerterize automatic **fault detection**

Structure and Operation of the Voter

- From each of the three inputs, subtract an equalization value
- Output is middle value of equalized values
- Equalization based on integration (has internal state)





Industrial Context of the Analysis

- **Legacy** model (~20 years old)
- Reverse engineering – **why** and **how** does it work ?
- Finding right **parameters** by testing is **very time consuming**
- Has been **qualified**, high confidence
- **Modifications** are made now
  - Better usage of Simulink
  - 4th input ?
- **New application** areas
- **No experience** in how to analyse it

Objectives of the Analysis

- Prove that a **transient peaks** cannot occur
  - Bounded-input bounded-output stability
- Choose good **parameters** for fault detection
  - a non-faulty sensor is never eliminated
- Experiment our **translator framework** on this kind of system
  - Feedback to implementors of proof engines

Equations of the Normal Operation Mode

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

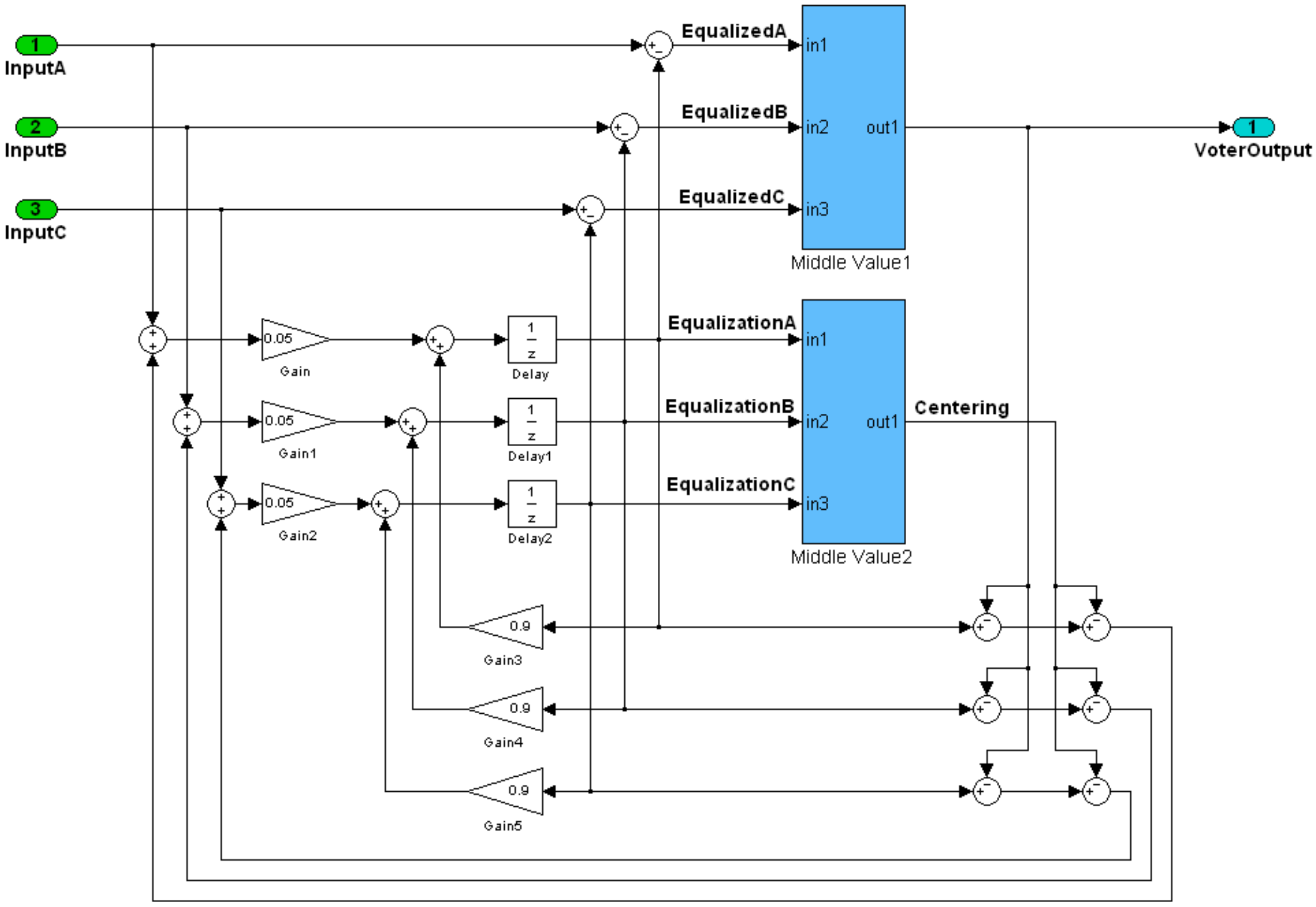
$$Centering_t = middleValue(EqualizationA_t, EqualizationB_t, EqualizationC_t)$$

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

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

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

MATLAB Simulink Model of the Voter



Questions for the Analysis

- Is this system **stable** if sensors are non-faulty, i.e. is the output always within some bound from the true value? *Bounded-Input-Bounded-Output stability*

- Is an **implementation** using floating point arithmetic stable? Can there be an **accumulation** of rounding errors, causing loss of stability / overflow?

- Observation: system is stable if Equalization values are bounded -> prove that **Equalization values** are bounded

Model Level Analysis Result

- Set MaxDev = 0.2 (typical value)
- Model level analysis can **prove stability**
- The following property can be found and proven **automatically:**

$$|EqualizationA| \leq 0.4 \text{ and}$$
$$|EqualizationB| \leq 0.4 \text{ and}$$
$$|EqualizationC| \leq 0.4$$

- Automated analysis based on the research results of our PhD student Adrien Champion

Key to Analysis Objectives : Inductive Invariant

For MaxDev = 0.2

|EqualizationA| ≤ 0.4
|EqualizationB| ≤ 0.4
|EqualizationC| ≤ 0.4

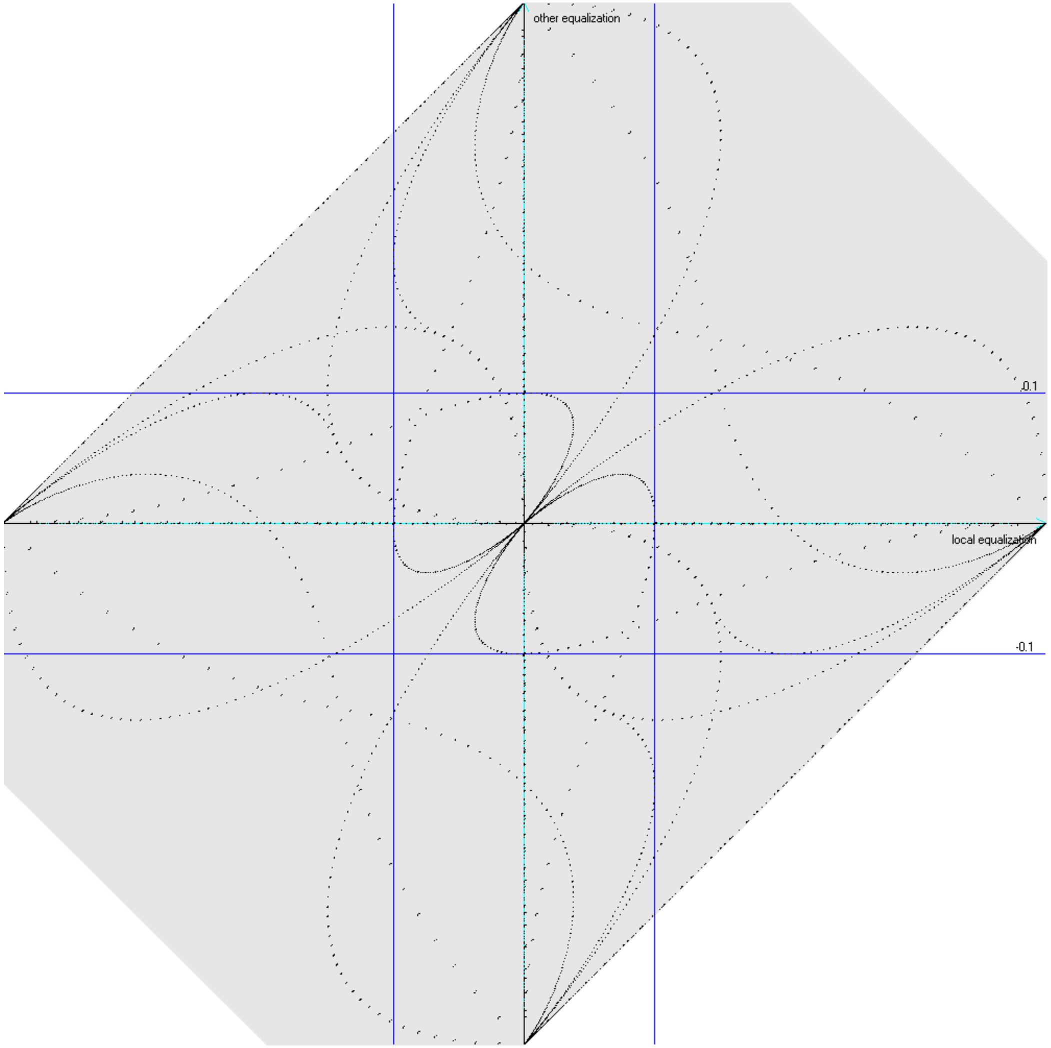
Proof objective

|EqualizationA - EqualizationB| ≤ 0.4
|EqualizationA – EqualizationC| ≤ 0.4
|EqualizationB – EqualizationC| ≤ 0.4

|EqualizationA + EqualizationB + EqualizationC| ≤ 0.66

Automatically generated lemmas

Inductive Octagonal Invariant



Code level analysis (floating point)

- Proof on model level assumes that no rounding errors occur
- In an implementation using floating point, rounding errors may accumulate
- **The invariant was partially confirmed on a C implementation using Astrée (abstract interpretation) based on the result from model checking**
  - **Combination of MC and AI**
- At the current state, a complete proof with Astrée is not possible
- Rounding errors can be over-approximated at model level, but this lacks scalability

Conclusion of this case study

Model-Checking is useful for proving properties of numerically complex systems and their floating point implementation

Systematic Industrial Application

- Despite the conclusive case studies, there is still no systematic application of model checking at RC

- **Why ?**

Obstacles to Systematic Application

- Still too much user skills required
  - Difficult for domain engineers
  - But there is progress in automated invariant generation
- Difficulty to express formal properties
  - But formal requirements engineering might help
- Scalability
  - Considerable progress in SMT solving
- Limited Scope
  - Lack of support for non-linear functions
- Cost is difficult to predict

Certification

- Objective: use analysis results as evidence for certification
- Not yet done today
- Enabled by latest standard DO-178C
- A research project is ongoing at RC with University of Iowa (Cesare Tinelli) based on the kind2 tool

Future Work: Cyber Security

- Cyber security of embedded systems is an issue
- Use model checking on cyber security requirements
- Prove the absence of security flaws in our systems
- We intend to initiate a collaborative project on the application of formal methods to cyber security

Further interests in formal methods at RC

- Combining analysis methods
  - PhD student, French research project CAFEIN
- Architectural analysis (AADL, SysML)
  - Participation in French « Project P », projects in the US
- Requirements engineering (generation of properties)
  - French research project co-submitted
- Automated Test Generation
  - Participation in ARTEMIS project MBAT

It's time for

Questions

Thank you for your attention