Model Checking of Aerospace Domain Models in an Industrial Context

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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
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

Simulink / StateFlow → Reactis → Lustre

NuSMV → ACL2 → PVS → Kind → Design Verifier → Tuff

SAL

Rockwell Collins/U of Minnesota → Esterel Technologies → SRI International → Reactive Systems → Rockwell Collins/U of Iowa → Rockwell Collins France/ONERA

Symbolic Model Checker → Bounded Model Checker → Infinite Model Checker
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

<table>
<thead>
<tr>
<th>Model</th>
<th>CPU Time (For NuSMV to Compute Reachable States)</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Mode1</td>
<td>&gt; 2 hours</td>
<td>11 sec</td>
</tr>
<tr>
<td>Mode2</td>
<td>&gt; 6 hours</td>
<td>169 sec</td>
</tr>
<tr>
<td>Mode3</td>
<td>&gt; 2 hours</td>
<td>14 sec</td>
</tr>
<tr>
<td>Mode4</td>
<td>8 minutes</td>
<td>&lt; 1 sec</td>
</tr>
<tr>
<td>Arch</td>
<td>34 sec</td>
<td>&lt; 1 sec</td>
</tr>
<tr>
<td>WBS</td>
<td>29+ hours</td>
<td>1 sec</td>
</tr>
</tbody>
</table>
Model Checking

CASE STUDIES
ADGS-2100 Adaptive Display & Guidance System

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

Modeled in Simulink
Translated to NuSMV
4,295 Subsystems
16,117 Simulink Blocks
Over $10^{37}$ Reachable States
ADGS-2100 Technology Transfer

**Iteration 1**
- Dev. Group (Blue)
  - Simulink R14 Model
  - Simulink R13 Model
  - SCADE Model
  - NuSMV Model
  - Translation Time: 1-4 Hours
  - Turnaround: 1 Day to 1 Week

**Iteration 2**
- Simulink R14 Model
- Reactis Model
- NuSMV Model
- Translation Time: 10 Minutes
- Turnaround: 3 Hours to 2 Days

**Iteration 3**
- Simulink R14 Model
- Reactis Model
- NuSMV Model
- Translation Time: 10 Minutes
- 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

Input Monitor

Failure Isolation

Failure Processing

Sensor Fusion
## CerTA FCS Phase I – Errors Found

Errors Found in Redundancy Manager

<table>
<thead>
<tr>
<th></th>
<th>Model Checking</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triplex Voter</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Failure Processing</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Reset Manager</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

- 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
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
• 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 $\text{MaxDev}$

- In our analysis, we assume that sensors are non-faulty

- Result allows to parameterize 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

\[
\text{Equalization} A_0 = 0.0 \\
\text{Equalization} B_0 = 0.0 \\
\text{Equalization} C_0 = 0.0 \\

\text{Centering}_t = \text{middleValue}(\text{Equalization} A_t, \text{Equalization} B_t, \text{Equalization} C_t) \\

\text{Equalized} A_t = \text{Input} A_t - \text{Equalization} A_t \\
\text{Equalized} B_t = \text{Input} B_t - \text{Equalization} B_t \\
\text{Equalized} C_t = \text{Input} C_t - \text{Equalization} C_t \\

\text{VoterOutput}_t = \text{middleValue}(\text{Equalized} A_t, \text{Equalized} B_t, \text{Equalized} C_t) \\

\text{Equalization} A_{t+1} = \text{Equalization} A_t + \\
0.05 \times (\text{sat}_0.5(\text{Equalized} A_t - \text{VoterOutput}_t) - \text{sat}_0.25(\text{Centering}_t)) \\
\text{Equalization} B_{t+1} = \text{Equalization} B_t + \\
0.05 \times (\text{sat}_0.5(\text{Equalized} B_t - \text{VoterOutput}_t) - \text{sat}_0.25(\text{Centering}_t)) \\
\text{Equalization} C_{t+1} = \text{Equalization} C_t + \\
0.05 \times (\text{sat}_0.5(\text{Equalized} C_t - \text{VoterOutput}_t) - \text{sat}_0.25(\text{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**:

  \[
  |\text{EqualizationA}| \leq 0.4 \text{ and } |\text{EqualizationB}| \leq 0.4 \text{ and } |\text{EqualizationC}| \leq 0.4
  \]

- 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  **Proof objective**
|EqualizationC| ≤ 0.4

|EqualizationA - EqualizationB| ≤ 0.4  **Automatically generated lemmas**
|EqualizationA - EqualizationC| ≤ 0.4
|EqualizationB - EqualizationC| ≤ 0.4

|EqualizationA + EqualizationB + EqualizationC| ≤ 0.66
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