Applying Model Checking to Large Software Specifications

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Embedded systems

• Software is increasingly pervasive
• No complex system is any longer built without software
  – Avionics, medical imaging and treatment, consumer electronics, appliances, ...

Problems

◆ Getting embedded systems to work properly is important
  – Safety-critical systems [comp.risks; Leveson, Safeware]
  – Pressures of the marketplace
◆ Getting them to work right is hard
  – Hard to clarify requirements
    » Problems that appear later cost far more to fix
  – Difficulties at the interfaces

Reactive systems

◆ Reactive systems are often specified (in part) by state machines that describe the actions that the system should make in response to an external event

Key question

◆ How do we increase our confidence that the requirements specification has the properties we want?
  – It does what it is supposed to do
  – It doesn’t do things it isn’t supposed to do

Symbolic model checking

◆ Evaluate temporal properties of finite state systems
◆ Extremely successfully for hardware verification
◆ Open question: applicable to large software specifications for reactive systems?
Software model checking

- Finite state software specifications
  - Reactive systems (avionics, automotive, etc.)
  - Hierarchical state machine specifications
    » Statecharts (Harel), RSML (Leveson)
- Goal: increase confidence in the correctness of the specification

Why might model checking fail?

- Software is often specified with infinite state descriptions
  - We don’t address those specifications
    » Jackson, Damon, Jha; Wing, Vaziri-Farahani; etc.
- Software specifications may be structured differently from hardware specifications
  - Hierarchy
  - Representations and algorithms for model checking may not scale

Our approach—try it!

- Applied model checking to the specification of TCAS II
  - Traffic Alert and Collision Avoidance system
    » In use on U.S. commercial aircraft
  - FAA adopted specification
  - Initial design and development by Leveson

Outline

- Hierarchical state machine specifications
- Symbolic model checking
- TCAS
- Our experiences in analyzing TCAS using model checking

Sample transitions

- **Trigger Event:** Temp_Update
  - Condition: Temperature in Too Hot
  - Output Action: Panic_Event

- **Trigger Event:** Temp_Update
  - Condition: Rod_Movement in Ready and Temperature in Hot
  - Output Action: Initiate_Move

- **Trigger Event:** Clock_Event
  - Condition: Rod_Movement in Just_Moved and
    \[ t = (t(entered(Just_Moved)) + Move_Delay) \]
  - Output Action: Move_Out

- **Trigger Event:** Rod_Update
  - Condition: Rod updates Rod_Config and Rod_Movement
  - Output Action: Rod_Updated
Events

- External—interactions with environment
- Synchrony hypothesis
  - External event arrives
  - Triggers cascade of internal events (micro steps)
  - Stability reached before next external event
- Technical issues with micro steps
  - Harel, Pnueli, Leveson

Properties to check: examples

- If Temperature is in Hot, then eventually Temperature is in Okay or Rod_Configuration is in All_In
- Rod_Configuration only changes in response to a Move_Finished event

TCAS

- http://www.faa.gov/and/and600/and620/newtcas.htm
- Warn pilots of traffic
  - Plane to plane, not through ground controller
  - On essentially all commercial aircraft
- Issue resolution advisories only
  - Vertical resolution only
  - Relies on transponder data

TCAS specification

- Irvine Safety Group (Leveson et al.)
  - Specified in RSML as a research project
  - FAA adopted RSML version as official
- Specification is about 400 pages long
- This study uses: Version 6.00, March 1993
  - Not the current FAA version

TCAS—high-level structure

- Own_Aircraft
  - Sensitivity levels, Alt_Layer, Advisory_Status
- Other_Aircraft
  - Tracked, Intruder_State, Range_Test, Crossing, Sense Descend/Climb

Model checking

- Does a temporal logic formula hold for a finite state machine?
  - If not, find counterexample
- Temporal logic
  - until, eventually, always, etc.
- For many logics, checking can be done in linear time in the size of the space state
  - Explicit model checking does this, exploiting symmetries for performance
Symbolic model checking

- State space can be huge (>\(2^{1000}\)) for many systems
- Use implicit representation
  - Data structure to represent transition relation as a boolean formula
- Algorithmically manipulate the data structure to explore the state space
- Key: efficiency of the data structure

Binary decision diagrams (BDDs)

- "Folded decision tree"
- Fixed variable order
- Many functions have small BDDs
  - Multiplication is a notable exception
- Can represent
  - State machines (transition functions)
  - Temporal queries

Using SMV

- SMV is a BDD-based model checker
- It checks CTL formulas
  - A specific temporal logic

Iterative process

- Iterate SMV version of specification
- Clarify temporal formula
- Model environment more precisely
- Refine specification

Use of non-determinism

- Inputs from environment
  - Altitude := {1000...8000}
- Simplification of functions
  - Alt_Rate := 0.25*(Alt_Barom-2P)/\(\Delta t\)
  - Alt_Rate := {-2000...2000}
- Unmodelled parts of specification
  - States of Other_Aircraft treated as non-deterministic input variables

Translating RSML to SMV

```
MODULE main
VAR
  state: {ON, OFF};
  on_event: boolean;
  off_event: boolean;
ASSIGN
  init(state) := OFF;
  next(state) := case
    state = ON & on_event : OFF;
  esac;
  off_event: OFF;
  state = OFF & on_event : ON;
  esac;
  state;
```
State encoding

- Flatten nested AND and nested OR states
- One variable for each OR state
  - An enumerated type of the alternatives
- VAR
  - S: \{A, B, C\}
  - T: \{D, E\}
  - U: \{F, G\}

Synchrony hypothesis

- Handling an external event

```plaintext
DEFINE
  Stable := !Initiate_Move & !Move_Finished & !Rod_Updated & !Clock_Event
ASSIGN
  next(Move_Finished) := case
    Stable : {0, 1};
    1  : 0;
  esac;
  ...for other external events...
```

Transitions

```plaintext
VAR RC: \{Out, Mid, In\};
ASSIGN
  T_Out_Mid : Mid;  T_Mid_In : In;
  T_Mid_Out : Out;  T_In_Mid : Mid;
  1 : RC;
esac;
```

Non-deterministic transitions

- A machine is deterministic if at most one of $T_{A,B}$, $T_{A,C}$, etc. can be true
- Else non-deterministic
- Can encode non-deterministic transitions
  ```plaintext
  next(S) := case
    T_{A,B} & T_{A,C}: \{B, C\};
    T_{A,B} : B;  T_{A,C} : C;
    1  : S;
esac;
  ```

Checking properties

- Initial attempts to check any property generated BDDs of over 200MB
- First successful check took 13 hours
  - Has been reduced to a few minutes
- Partitioned BDDs
- Reordered variables
- Implemented better search for counterexamples

Property checking

- Domain independent properties
  - Deterministic state transitions
  - Function consistency
- Domain dependent
  - Output agreement
  - Safety properties
- We used SMV to investigate some of these properties on TCAS’ Own_Aircraft module
Disclaimer

The intent of this work is to evaluate symbolic model checking of state-based specifications, not to evaluate the TCAS II specification. Our study used a preliminary version of the specification, version 6.00, dated March, 1993. We did not have access to later versions, so we do not know if the issues identified here are present in later versions.

Deterministic transitions

- Do the same conditions allow for non-deterministic transitions?
- Inconsistencies were found earlier by other methods [Heimdahl and Leveson]
  - Identical conditions allowed transitions from Sensitivity Level 4 to SL 2 or to SL 5
- Our formulae checked for all possible non-determinism; we found this case, too

Tradeoffs

- Our approach was slower than the Heimdahl & Leveson approach
- Their approach reported some false positives

Function consistency

- Many functions are defined in terms of cases
- A function is inconsistent if two different conditions $C_i$ and $C_j$ are true simultaneously

Display_Model_Goal

- Tells pilot desired rate of altitude change
- Checking for consistency gave a counterexample
  - Other_Aircraft reverse from an Increase-Climb to an Increase-Descent advisory
  - After study, this is only permitted in our non-deterministic modelling of Other_Aircraft
  - Modelling a piece of Other_Aircraft's logic precludes this counterexample
Output agreement

- Related outputs should be consistent
  - Resolution advisory
    - Increase-Climb, Climb, Descend, Increase-Descend
    - Display_Model_Goal
    - Desired rate of altitude change
  - Between -3000 ft/min and 3000 ft/min
  - Presumably, on a climb advisory, Display_Model_Goal should be positive

Output agreement check

- AG (RA = Climb -> DMG > 0)
  - If Resolution Advisory is Climb, then Display_Model_Goal is positive

- Counterexample was found
  - t_0: RA = Descend, DMG = -1500
  - t_1: RA = Increase-Descend, DMG = -2500
  - t_2: RA = Climb, DMG = -1500

Where may formulae come from?

“There have been two pilot reports received which indicated that TCAS had issued Descend RA’s at approximately 500 feet AGL even though TCAS is designed to inhibit Descent RAs at 1,000 feet AGL. All available data from these encounters are being reviewed to determine the reason for these RAs.”

--TCAS Web site

Performance results

<table>
<thead>
<tr>
<th>Property</th>
<th>Time (secs)</th>
<th>#BDD nodes</th>
<th>Memory (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition Consistency</td>
<td>387</td>
<td>717K</td>
<td>16.4</td>
</tr>
<tr>
<td>Function Consistency</td>
<td>289.5</td>
<td>387K</td>
<td>11.5</td>
</tr>
<tr>
<td>Step Termination</td>
<td>57.2</td>
<td>142K</td>
<td>7.4</td>
</tr>
<tr>
<td>Descend Inhibit</td>
<td>166.8</td>
<td>429K</td>
<td>11.8</td>
</tr>
<tr>
<td>Increase-Descend</td>
<td>193.7</td>
<td>282K</td>
<td>9.9</td>
</tr>
<tr>
<td>Output Agreement</td>
<td>325.6</td>
<td>376K</td>
<td>11.6</td>
</tr>
</tbody>
</table>

- Sun SPARCStation 10 with 128MB
- SMV Release 2.4.4

Discussion

- A positive data point for applying model checking to state based software specifications
- Iterative use of model checking promising
  - Refine and debug specification
  - Explicit clarification of interfaces
  - Regression testing of specifications

Discussion

- What are the limits?
  - Specification size
    - We produce around 200 boolean variables, about the edge of what SMV can handle
  - Numerical issues (multiply, divide, etc.)
    - Needed to refine Other_Aircraft
  - Desirable properties to check?
- Domain expertise is critical
  - Thanks, Jon!
Discussion

- Differences in applying to software and to hardware?
  - Word-level vs. bit-level?
  - Event structure? Synchrony hypothesis?
  - Properties to check?
  - Timing properties?

Model checking software

- Theory
- Software Engineering
- Hardware
- Domain
- Expertise

Displayed.Model.Goal =

0

Max(OwnTrackAltRate, If Composite.A not in state Positive
PRIVATE(Displayed.Model.Goal), 1000 ft/min)

Min(OwnTrackAltRate, If (New.Climb or New.Threat) and
PRIVATE(Displayed.Model.Goal), -1000 ft/min)

3500 ft/min If New.Increase.Climb
-2000 ft/min If New.Increase.Descend
1300 ft/min If Incl.Increase.Climb, Cancelled and
not New.Increase.Climb and
not Composite.A in state Positive

utra(Displayed.Model.Goal) Otherwise