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Utilization of Simulink Verification and Validation (V&V) and Simulink Design Verifier (SDV) for HVAC Controls Software

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HVAC Controls Algo And Readiness, Electronic Controls and Software Engineering, General Motors Technical Centre India Pvt. Ltd., Bengaluru, India
Outline

- Readiness Testing and Core Algorithm work overview
- HVAC Production-oriented testing (ECU, model)
- What is structural coverage? Why use it?
- What are model coverage metrics?
- Overview of work done and results
- Recommendations for incremental improvements
- Potential for Automatic Test case Generation
- Potential for Property Proving
- Current challenges and some proposed workflows
HVAC Control Software

Regulates the *air temperature, flow rate and moisture* throughout the vehicle interior (by considering the effects of *ambient temperature, sun load, and heat transfer mechanisms*) in real-time

Challenges overcome using Model-Based Designs in Development

- Unit level and integrated software verified early
- Same software deployed to many different vehicles by simply calibrating parameters such as vehicle dimensions
- Same s/w also deployed to multiple controllers with varying hardware and software architecture (Non-standard or standard ones like AUTOSAR)
- Integration of legacy software and the model-based software possible for vehicles nearing production
- Parallel development of several components possible
- Production code auto-generated, compiled and targeted efficiently and accurately
HVAC Control Software – Example Components

- **Aero Shutter Control**
  - Combinational logic for on/off control of magnetically driven set of flaps which close front end airflow paths to enhance vehicle aerodynamics

- **Cabin Air Recirculation Control**
  - Physics-based design to ensure minimal compressor work while maintaining thermal comfort of the occupants
  - Repeated calculations (physical properties) implemented by creating and using our own library blocks
  - Functional verification using approximate plant model for closed-loop simulation
  - Standard test inputs derived from requirements and vehicle like scenarios (vehicle test data)
Current Testing in Production

Test cases mainly guided by Requirements

Both Manual and Automated Testing
Simulation Model Testing
- Performed at the unit level
- Closed-loop simulation of the control system with approximate plant model
- Detailed functional verification based on requirements, internal standards and over several vehicle like scenarios
- Performed using standard test inputs developed once

CPP Unit Testing
- Simulation model I/Os are automatically translated using a MATLAB M-script
- Verifies interface between the automatically generated code from the model and the wrapper interface code and the buried conversion mathematics
- Performs acceptance check for example, requirements, rounding errors etc. with the use of CPP asserts

Plant models for closed-loop simulation
Simulation and early verification possible
Readiness Group

Regression Test
- Detailed Component level verification
- Performed once on a Model Year Software
- Performed using automated test scripts on dSPACE HIL

Delta Change Verification
- Verifies the specific delta change on every release
- Manual / automated test scripts

Acceptance Test
- Verifies the system level functionalities on every release
- Performed using automated test scripts on dSPACE HIL

Testing of HVAC components at the integrated ECU
Shift towards early model-based V&V
Structural Coverage

The output shall be set to 100 times the sensor input.

\[ I_1 \rightarrow O \]

Sample inputs: -15, 10, 45
Boundary values: -5, -4.9, 40, 40.1

-5 \leq I_1 \leq 40

If sensor input is valid, the output shall be 100 times, else a fail safe value of 180 should be output.

\[ I_2 \rightarrow O \]

Valid and invalid cases also

\[ I_1 \rightarrow O \]

Choices of input values affect the calculations done downstream
Overall coverage gets influenced by such choices!
Real-life Requirements: Numerous; In Natural Language

Irrespective of the test design techniques, in real-life scenario, model coverage assessment becomes necessary and crucial!
Why Structural Coverage?

- Find out gaps in requirements-based test cases
- Identify gaps in requirements
- Identify unreachable parts of the model (or code)
- Identify unintended functionality

ISO/FDIS 26262-6:2010(E)

Table 12 — Structural coverage metrics at the software unit level

<table>
<thead>
<tr>
<th>Methods</th>
<th>ASIL A</th>
<th>ASIL B</th>
<th>ASIL C</th>
<th>ASIL D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Statement coverage</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>1b Branch coverage</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>1c MC/DC (Modified Condition/Decision Coverage)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

NOTE 2 In the case of model-based development, the analysis of structural coverage can be performed at the model level using analogous structural coverage metrics for models.
Structural Coverage Assessment

Principle

Practice for Production

Relevant Mathworks toolbox:
Simulink Verification and Validation toolbox (V&V toolbox)
Model Coverage Metrics – Condition Coverage

- Condition Coverage
  - Analyzes blocks that output logical combinations of their inputs
  - Logical Operator blocks, Stateflow transitions

2 AND blocks; 2*2, 3*2
Cal value was T in all test cases
Model Coverage Metrics – Condition Coverage

No True for one of the AND conditions
=> making it T will cover 2 more conditions (for the AND, OR together)
Model Coverage Metrics

- Decision Coverage
  - Analyzes model elements that represent decision points
  - Switch block, Stateflow states
Model Coverage Metrics

- **MCDC**
  - Independence of logical block inputs and transition conditions

```
function FUNC=f1
V1_Err < K1_Min && ...
K1_Max > V2
FUNC=F;

function FUNC=T;
```

### Stateflow Graphical Function

<table>
<thead>
<tr>
<th>Stateflow</th>
<th>Graphical Function with a condition of the form <strong>C1 &amp;&amp; C2</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CC</strong></td>
<td>75% (3/4)</td>
</tr>
<tr>
<td>C1</td>
<td>V1_Err &lt; K1_Min</td>
</tr>
<tr>
<td>C2</td>
<td>K1_Max &gt; V2</td>
</tr>
<tr>
<td><strong>DC</strong></td>
<td>100% (2/2)</td>
</tr>
<tr>
<td><strong>MCDC</strong></td>
<td>50% (1/2 conditions reversed the outcome)</td>
</tr>
<tr>
<td>C1</td>
<td>V1_Err &lt; K1_Min</td>
</tr>
<tr>
<td>C2</td>
<td>K1_Max &gt; V2</td>
</tr>
<tr>
<td>Out</td>
<td>C1 &amp;&amp; C2</td>
</tr>
</tbody>
</table>
Overview of automation done around V&V toolbox

MATLAB M Scripts for automation around the utilization of the Simulink V&V toolbox for structural coverage assessment

Recommendations to improve test cases

- Set V1 > K1: function f1 will get 100% CC (See sheet f1)
- Set V2_MinMxAirSetPt > K2: function f2 gets 100% CC (See sheet Other Graphical Funcs 50%)
- Set V3_MaxMxAirSetPt > K3-C1: function f3 gets 100% CC (See sheet Other Graphical Funcs 50%)
- V4 >= K4: function f4 will get 100% CC (See sheet f4)

- Set V5 to 9, 12, 20 and 28: Distribution modes D5, D7, D8 and D12 will be reached
- Modify speed values in Test 6 Sub Test 9: Covers Transition TRANSxyz
- Change Validity value V5 to True from False in Test 7 SubTest 2: Achieves the goals for this test case
- Look into cal. and/or validity values for Test 7 SubTests 3 to 10: Reaches various substates of STATEabc
- Correction needed for test cases Test 3 SubTest 1: K1 is being set to 100000 but it's max. is defined as 15000 in the spec.
- K2 has to be set to 0 for some test cases so that states transitions such as from STATE_S1 to STATE_COOL_DOWN, STATE_COOL_DOWN to STATE_NORMAL, STATE_NORMAL to STATE_INIT become possible.

Overview of automation done around V&V toolbox:

1. Original Test Cases
2. For each test case, automatically create variables in the simulation environment
3. Automatically simulate the design model with appropriate settings
4. Automatically collect structural coverage data including cumulative coverage
5. Extract and provide hints to engineers to improve the original set of test cases with new test cases

- Internal tool for test automation
- Excel sheet textual description of steps

Additional state coverage

Test Cases: C12 Test Cases - adapted from HIL test cases
Component: C12 Test Cases - adapted from HIL test cases
Software: V1, V1.1 (new)
Requirements Document: HVAC Control - C12

Date: 27-Jun-11
Tester Name: Arun Rao

Condition Coverage CC

S1
S11
S111
S1111
S1112
S1113
S1114
S1115
S11151
S11152
S1116
S11161
S11162
S112
S1121
S1122
S113
S2
S21
S22
S23
S3
S31
S32
S33

V1 = f1
V1 = T;
V1_Err < K1_Min
K1_Max > V2
Out C1 && C2
T Out F Out
C1 TT Fx
C2 TT (TF)

Excel sheet textual description of steps

MATLAB M Scripts

Internal tool for test automation

Recommendations to improve test cases
# Coverage Analysis Report

## Project Information

<table>
<thead>
<tr>
<th><strong>Project name</strong></th>
<th>HVAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tester Name</strong></td>
<td>Arun Rao</td>
</tr>
<tr>
<td><strong>Requirements</strong></td>
<td>HVAC Control - C12</td>
</tr>
<tr>
<td><strong>Test Cases</strong></td>
<td>C12 Test Cases - adapted from HIL test cases</td>
</tr>
<tr>
<td><strong>Component</strong></td>
<td>C12 Test Cases - adapted from HIL test cases</td>
</tr>
<tr>
<td><strong>Software</strong></td>
<td>V1, V1.1 (new)</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>27-Jun-11</td>
</tr>
</tbody>
</table>

## Condition Coverage

![Condition Coverage Graph](image)

- **Low coverage here!**
# Recommendations

## Sample recommendations for C12, C8, C2, C1

<table>
<thead>
<tr>
<th>Srl. No.</th>
<th>Recommendation</th>
<th>Expected effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Set V1 &gt; K1</td>
<td>function f1 will get 100% CC (See sheet f1)</td>
</tr>
<tr>
<td>2</td>
<td>Set V2_MinMxAirSetPt &gt; K2</td>
<td>function f2 gets 100% CC (See sheet Other Graphical Funcs 50%)</td>
</tr>
<tr>
<td>3</td>
<td>Set V3_MaxMxAirSetPt &gt; K3-C1</td>
<td>function f3 gets 100% CC (See sheet Other Graphical Funcs 50%)</td>
</tr>
<tr>
<td>4</td>
<td>V4 &gt;= K4</td>
<td>function f4 will get 100% CC (See sheet f4)</td>
</tr>
<tr>
<td>5</td>
<td>K2 has to be set to 0 for some test cases so that states transitions such as from STATE_S1 to STATE_COOL_DOWN, STATE_COOL_DOWN to STATE_NORMAL, STATE_NORMAL to STATE_INIT become possible.</td>
<td>Additional state coverage</td>
</tr>
<tr>
<td>6</td>
<td>Set V5 to 9, 12, 20 and 28</td>
<td>Distribution modes D5, D7, D8 and D12 will be reached</td>
</tr>
</tbody>
</table>

1. Modify speed values in Test 6 Sub Test 9 - Covers Transition TRANSxyz
2. Change Validity value V5 to True from False in Test 7 SubTest 2 - Achieves the goals for this test case
3. Look into cal. and/or validity values for Test 7 SubTests 3 to 10 - Reaches various substates of STATEabc
4. Correction needed for test cases Test 3 SubTest 1: K1 is being set to 100000 but it's max. is defined as 15000 in the spec.
## Coverage for various components

<table>
<thead>
<tr>
<th>Srl. No.</th>
<th>Component</th>
<th>Ver</th>
<th>Total test cases</th>
<th>CC</th>
<th>Cyclomatic Complexity</th>
<th>Total Conditions in the Model</th>
<th>Conditions Covered by Test Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1</td>
<td>v2</td>
<td>15</td>
<td>94</td>
<td>7</td>
<td>54</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>C2</td>
<td>v1</td>
<td>25</td>
<td>83</td>
<td>37</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>C3</td>
<td>v2</td>
<td>3</td>
<td>83</td>
<td>49</td>
<td>196</td>
<td>162</td>
</tr>
<tr>
<td>4</td>
<td>C4</td>
<td>v2</td>
<td>32</td>
<td>66</td>
<td>55</td>
<td>412</td>
<td>270</td>
</tr>
<tr>
<td>5</td>
<td>C5</td>
<td>v2</td>
<td>6</td>
<td>65</td>
<td>57</td>
<td>54</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>C6</td>
<td>v2</td>
<td>10</td>
<td>76</td>
<td>94</td>
<td>130</td>
<td>99</td>
</tr>
<tr>
<td>7</td>
<td>C7</td>
<td>v2</td>
<td>30</td>
<td>86</td>
<td>100</td>
<td>404</td>
<td>346</td>
</tr>
<tr>
<td>8</td>
<td>C8</td>
<td>v1</td>
<td>60</td>
<td>57</td>
<td>101</td>
<td>116</td>
<td>66</td>
</tr>
<tr>
<td>9</td>
<td>C9</td>
<td>v2</td>
<td>28</td>
<td>48</td>
<td>130</td>
<td>164</td>
<td>78</td>
</tr>
<tr>
<td>10</td>
<td>C10</td>
<td>v1</td>
<td>21</td>
<td>76</td>
<td>139</td>
<td>372</td>
<td>283</td>
</tr>
<tr>
<td>11</td>
<td>C11</td>
<td>v2</td>
<td>55</td>
<td>65</td>
<td>211</td>
<td>674</td>
<td>437</td>
</tr>
<tr>
<td>12</td>
<td>C12</td>
<td>v1</td>
<td>47</td>
<td>83</td>
<td>234</td>
<td>316</td>
<td>262</td>
</tr>
<tr>
<td>13</td>
<td>C13</td>
<td>v2</td>
<td>14</td>
<td>70</td>
<td>275</td>
<td>858</td>
<td>604</td>
</tr>
<tr>
<td>14</td>
<td>C14</td>
<td>v2</td>
<td>55</td>
<td>68</td>
<td>302</td>
<td>302</td>
<td>204</td>
</tr>
<tr>
<td>15</td>
<td>C15</td>
<td>v2</td>
<td>165</td>
<td>51</td>
<td>322</td>
<td>528</td>
<td>268</td>
</tr>
<tr>
<td>16</td>
<td>C16</td>
<td>v1</td>
<td>53</td>
<td>61</td>
<td>353</td>
<td>758</td>
<td>460</td>
</tr>
</tbody>
</table>
Coverage for various components
Some learnings – Simulink V&V toolbox

- Original test cases created for the hardware bench/HIL
- Extra effort to recreate test cases; capture intention of the tester
- Solution for the future: Model-level test cases to be updated/created/maintained for Readiness testing
- Utilization of the results requires some extra effort and time from component owners
- Ideally suited for independent V&V activities to assist Production work and teams initially
Some key take-always

- Some components might have a very good coverage already
  - > 80% Condition Coverage
  - Small models/low complexity: C1, C2, C3
  - Test cases have evolved well over time: C7, C12

- Some components have lower coverage
  - Only around (50%-60%)
  - Larger models/higher complexity
  - Much large number of test cases also haven’t helped; so, gaps are important

Irrespective of the above, structural coverage assessment is necessary!

Improvements can only happen after assessment!
Simulink Design Verifier (SDV) toolbox

- SDV – Automatic Test Generation (ATG)
  - The toolbox can generate test cases automatically as per user-defined coverage requirements

- SDV – Property Proving (PP)
  - A technique to check if the model satisfies critical requirements without writing numerous test cases
Use Simulink Design Verifier for Automatic Test case Generation!!
Use Simulink Design Verifier ATG capability to improve test cases further
Some points to note

- ATG test cases to supplement existing test cases
  - First assess coverage of existing test cases
  - Identify gaps to increase coverage via self-designed test cases if desired
  - Use SDV ATG for even further improvements

- Existing models
  - May have unsupported constructs; Use automatic stubbing
  - May encounter some scalability issues

- Use ATG for selective models/subsystems
  - Where complexity is involved
  - To find out if any parts of the model are unreachable
Design Verification

Principle

- Model
- Property (Assertion)
- Design Verification Tool
- Yes/No

Yes – Guaranteed that the property holds for all possible scenarios
No – Generates a simulation trace showing the violation

Practice for Production

- Requirements in Word, DOORS, etc.
- Design model in a modeling language
- Identify relevant requirements
- Identify relevant design decisions
- Properties specified in the format required by the tool
- Model with some changes for tool compatibility
- Expected result?
- Design Verification Tool
- Unexpected result?
- Consult the designer to revise design/property
- Done

Relevant Mathworks toolbox: Simulink Design Verifier (SDV)
Aero Shutter is never closed if the speed is less than 50 kmph.

Always, if the Aero Shutter is closed, it implies that the coolant temperature is less than some defined maximum (92 degC).

Once ON, heater coolant pump should remain ON for at least 30s even if the request becomes FALSE in the meantime.
Indicate some workflows for V&V and SDV toolboxes through short demos
Final Conclusions

- Structural coverage assessment using the V&V toolbox important to improve on test cases
- Standards recommend it - not just for critical applications
- Workflows could be tailored and adopted to suit particular production environments
- SDV toolbox capabilities could be used to improve test cases via ATG for uncovered objectives
- In addition, Property Proving feature of the SDV toolbox complements traditional testing approaches to increase overall confidence