MathWorks
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CONFERENCE 2016

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A Unified Approach to Model and Code Verification

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Motivation

- Most controls applications are a combination of model-based generated code and hand code
- How do I efficiently test this mix of hand code and generated code?
- MathWorks has tools for testing models and tools for testing code
- Is there a workflow for me to use these tools in a complementary, optimum way?
Case Study: Cruise Control Application

Objective: set cruise control target speed and pedal position based on driver & vehicle inputs

Cruise Control Application (C code)
- Hand code components
- Model-based Stateflow component
- Model-based S-function component

65 mph
Case Study: Cruise Control Architecture

**System Inputs**
- Cruise Power
- Brake
- Vehicle Speed
- Coast/Set
- Accel/Resume

**Function Scheduler**
- Read Inputs
- Fault Logging
- Target Speed Control Module
- Pedal Command Control Module
- Write Outputs

**System Outputs**
- Target Speed
- Engaged
- Pedal Position

**Control Module**
Case Study: Roles & Workflow

- **MBD Controls Guy: Chuck**
  - Develops modules using Simulink models
  - Integrates C code with models via s-functions
  - Generates the code
  - Relies on model-based testing methods

- **Integration & Build Guy: Anthony**
  - Develop C code modules by hand
  - Integrates hand code and generated code
  - Creates the ECU build
  - Relies on the HiL bench for testing
Case Study: Deliver First Production Release to Customer

To deliver our first production release we will need the following new features/changes:

- Move signals/cals from floats to integers in Target Speed Module
- Include customer lookup table code in Pedal Command to support calibration
- Demonstrate generated code is MISRA compliant
- Remove unused fault record
- Migrate the code to run on customer’s ECU (14-bit to 12-bit ADC)

In addition to the changes we will need to provide functional test results for the model-based modules and the integrated code.
Case Study: Workflow

Hand Code

- Software requirements
- Architectural design specification
- Unit design specification
- (Manual) implementation
- (Hand-written) C/C++ code

MBD Generated Code

- Software requirements
- Executable specification
- Model used for production code generation
- Generated C/C++ code

S-function Code

- Integrate as s-function
- Pedal Command Control Module

Cruise Control Application

- Read Inputs
- Fault Logging
- Write Outputs

Target Speed Control Module
Model-based Design Tasks

First let’s focus on the model-based design tasks and what checks are available:

- Convert signals/cals from floats to integers in Target Speed Module
- Include the customer lookup table in the Pedal Cmd to support calibration
- Demonstrate generated code is MISRA compliant

Our approach will be to do checks before functional testing, early in the development to minimize re-work.
Simulink Design Verifier identifies design errors on the model.
These “dead logic” errors would prevent successful functional testing.
Root Cause Analysis/Fix of Dead Logic

- **Dead logic** due to “uint8” operation on `incdec/holdrate*10`
- **Fix** change the order of operation `10*incdec/holdrate`

Design Error Detection reveals this condition can never be false!
Model-based Design Tasks

*First let’s focus on the model-based design tasks and what checks are available:*

- Convert signals/cals from floats to integers in Target Speed Module
- Include the customer lookup table in the Pedal Cmd to support calibration
- Demonstrate generated code is MISRA compliant

*Our approach will be to do checks before functional testing, early in the development to minimize re-work*
Import Hand Code into the Model (S-Function)

Legacy Code Tool imports the hand code into an s-function block and creates a tlc file for code generation.
Customer Lookup Table: Checking the S-Function Code for Runtime Errors

Pointer access out of bounds (Impact: High)
Attempt to dereference pointer at index 11.
Valid range: [0 .. 10]
Root Cause Analysis/Fix of S-Function Run-time Errors

/* Definition for custom storage class: Global */

real32_T PedalCmdY[11] = { 0.0F, 0.5F, 1.0F, 1.5F, 2.0F, 2.5F,
                         3.0F, 3.5F, 4.0F, 4.5F, 5.0F } ;

int8_T SpeedDelX[11] = { -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 } ;

float Lookup1D_C(char u, char const X[], float const Y[])
{
    float y = 0.0f;
    unsigned char index = 0;
    float temp = 0.0f;
    unsigned char mySize = 11;

    if (engaged) {
        PedalPos = Lookup1D_C((int8_T)rtb_Sum, (int8_T*)(&SpeedDelX[0]),
                               (int8_T)rtb_Sum, (int8_T*)(&SpeedDelX[0]));
    } else {
        PedalPos = 
    }

    while((u >= X[index]) && (index < mySize))
    {
    }

    else
    {
        while((u >= X[index]) && (index < (mySize-1)))
        {
            index++;
        }
        if (index > 0)
Model-based Design Tasks

First let’s focus on the model-based design tasks and what checks are available:

- Convert signals/cals from floats to integers in Target Speed Module
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Checking **Model for MISRA compliance with Model Advisor**

Target Speed Control Module
Checking Model for MISRA compliance with Model Advisor
Checking Model for MISRA compliance with Model Advisor

- Checks model design and code configuration settings
- Increases likelihood of generating MISRA C:2012 compliant code
Configuring Polyspace from the Model
Launching Polyspace from the Model
Review Bug Finder MISRA results

MISRA AC AGC 8.10 (Obligatory)

All declarations and definitions of objects or functions at file scope shall have internal linkage unless external linkage is required. Variable 'AccelResSw' should have internal linkage.

PolySpace Bug Finder - CruiseControl_PS C:\Demo\VnV\VnV_Wkshp

Results Summary

Showing 18/18

MISRA AGC 18

1 Environment 4

8 Declarations and definitions 14

Category: Obligatory CruiseControl_PS.c Global

CruiseControl_PS.c

39

/** Definition for custom switch **/

boolean_T AccelResSw;

40

boolean_T Brake;

41

boolean_T CoastSeSw;
Reduce MISRA violations with “Code Placement” setting

- Data definition: Data defined in a single separate source file
- Data definition filename: cruise_control_global.c
- Data declaration: Data declared in a single separate header file
- Data declaration filename: cruise_control_global.h
- #include file delimiter: Auto

Global data placement (MPT data objects only)
- Signal display level: 10

Target Speed Control Module
Justify other violations by adding annotation

```c
30  DW_CruiseControl_PS_T DW;
32  /* Real-time model */
33  RT_MODEL_CruiseControl_PS_T M_;
34  RT_MODEL_CruiseControl_PS_T *const M = &M_;
```
Model-based Design Tasks

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Our approach will be to do checks before functional testing, early in the development to minimize re-work
Model-based Design Tests

All checks are complete, we will need to provide test results for the model-based modules:

- Functional testing of s-function based Pedal Command module
- Equivalence (model-to-code) testing of the Target Speed module
Functional Testing of Pedal Command (S-Function)

- Coverage analysis for the model and the s-function code.
- Unable to achieve full coverage due to “defensive” programming.

Uncovered Links:

<table>
<thead>
<tr>
<th>Metric</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision (D1)</td>
<td>100% (2/2) decision outcomes</td>
</tr>
<tr>
<td>Condition (C1)</td>
<td>75% (3/4) condition outcomes</td>
</tr>
</tbody>
</table>

Conditions analyzed:

<table>
<thead>
<tr>
<th>Description</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u \geq X[index]$</td>
<td>105</td>
<td>21</td>
</tr>
<tr>
<td>$index &lt; (mySize-1)$</td>
<td>105</td>
<td>0</td>
</tr>
</tbody>
</table>
Model-based Design Tests

All checks are complete, we will need to provide test results for the model-based modules:

- Functional testing of s-function based Pedal Command module
- Equivalence (model-to-code) testing of the Target Speed module
Check the Generated Code for Equivalent Model Behavior

- Integrated SIL mode support for model-to-code equivalence testing
- Coverage report for generated code for a detailed equivalence analysis
Model-based Design Tests

All checks are complete, we will need to provide test results for the model-based modules:

- Functional testing of s-function based Pedal Command module
- Equivalence (model-to-code) testing of the Target Speed module
Integrated Code Testing

The hand code design tasks:

- Remove unused fault record
- Migrate the code run on customer’s ECU (14-bit to 12-bit ADC)

The minor hand code changes have been made.

An ECU build was created based on the integration of hand code and generated code.

We now need to provide functional test results for the integrated code on the HiL bench.

Find issues that result from the integration of tested modules from hand code, s-function code and model-based generated code.
Issues Found on HIL Bench…

- The Cruise Control powered off during fault testing
- And, the Target Speed never exceeded 40 mph
Creating a Code Prover project to check the Integrated Code

- Read Inputs
- Write Outputs
- Scheduler
- Fault Logging

- Target Speed Control Module
- Pedal Command Control Module

Target Speed

Control Module

Pedal Command
Control Module

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Code Integration Check with Polyspace:
Non-terminating loop in Hand Code

SysTick_Handler.c ➔ scheduler_executive.c ➔ monitor_build_in_test_faults.c ➔ fault_log.c

SysTick_Handler ➔ scheduler_executive ➔ monitor_build_in_test_faults ➔ fault_log ➔ NTL

/* Store the current fault into circular buffer */
for (ix = 0; ix <= 12u; ix++)
{
    FaultInfoElement[FaultRecIndexCntr + ix] = *pFlt;
    *pFlt = 0x0u;
    pFlt++;
}

? Illegally dereferenced pointer ?
Warning: pointer may be outside its bounds
Dereference of local pointer 'pFlt' (pointer to unsigned int 32, size: 32 bits):
    Pointer is not null.
    Points to 4 bytes at offset multiple of 4 in [0 .. 40] in buffer of 40 bytes, so may be outside bounds.

! Non-terminating loop ?
The loop is infinite or contains a run-time error.
loop may fail due to a run-time error (maximum number of iterations: 11)
Cause of Cruise Control Powering off during fault testing

```c
void fault_log(FAULT_LOG_INFO_T *pFaultInfo)
{
    uint32_t ix;
    uint32_t *pFlt = (uint32_t *)pFaultInfo;

    /* Validate current fault index counter */
    if (FaultRecIndexCntr >= (MAX_FAULT_LOG_INFO_SIZE - 12u))
    {
        FaultRecIndexCntr = 0x0u;
    }

    /* Store the current fault into circular buffer */
    for (ix = 0; ix < 12u; ix++)
    {
        FaultInfoElement[FaultRecIndexCntr + ix] = *pFlt;
        *pFlt = 0x0u;
        pFlt++;
    }

    /* Update the circular buffer fault index counter */
    FaultRecIndexCntr += ix-1;
}
```
Vehicle speed signal propagated to “CruiseControl_PS.c” [0 ... 40]

```c
} else if (Speed > maxtspeed) {
    /* Transition: '<S1>:114' */
    /* Exit Internal 'ON': '<S1>:54' */
    DW.is_ON = CruiseControl_IN_NO_ACTIVE_CHILD;
    DW.is_CRUISE = CruiseControl_PS_IN_STANDBY;
    /* Entry 'STANDBY': '<S1>:52' */
    engaged = false;
```
Root Cause for Dead Code: Speed Sensor Input Hand Code

Changing analog-to-digital converter from 14 to 12-bit results in dead code

MASK – accounts for scaling down for new ADC from 14-bit to 12-bit

Overlooked changing CONV_FACTOR for new ADC

/* Conversion factors of speed */
#define NEW_ECU
#if defined NEW_ECU
#define SPEED_MASK 0xFFF
#else
#define SPEED_MASK 0x3FF /* Original design specification */
#endif

/* Scaling for conversion factor for translating sensor input to miles/hr */
#define CONV_FACTOR 0.01 /* FAILS */

#define MAX_AI_RAW_COUNTS _BUFFER_SIZE 10

// e.g., 0.53 = (AI_Speed.Ser0, _CONV_FACTOR, _SPEED_MASK, _AI_SPEED)

/* Convert raw counts to speed */
AI_Speed.Speed = ((AI_Speed.Average & SPEED_MASK) * CONV_FACTOR);

/* Updated analog inputs */
MDB_Shared_Data.Speed = AI_Speed.Speed;
Workflow Summary: Complementary Model & Code Verification

- Hand Code → (Hand-written) C/C++ code

- Check model early for design errors
- Check MISRA compliance (Mdl Advisor)

- Functional testing (simulation)

- Code coverage (SIL)

- SIL mode support

- Check integrated code for run-time errors

- Check s-function code for run-time errors
- Check MISRA compliance (Polyspace)
A Complementary Model and Code Verification Process …

- Model and code checks before functional testing to minimize rework
- Perform functional, dynamic testing with model and code structural analysis with automation, and reuse of test assets
- Analyze the code to find issues resulting from the integration of
  - hand code
  - s-function code
  - model-based generated code
- Includes formal methods analysis to go beyond functional testing
- Enables more, early testing of the model and code
- Continual increase in design confidence
Thank You!