Automatic test data generation for time-continuous embedded system using built-in signals

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Abstract: Nowadays, embedded systems are becoming critical applications and play important roles in modern society. Therefore, quality assurance for these types of systems has attracted many attentions in software engineering research and development community. In these systems, testing procedure needs high coverage criteria such that test data cover all possible run. However, it is difficult to generate test data to coverage all possible runs due to the complex embedded system. In this paper, we propose a method to automatically generate test data based on built-in source signal in order to obtain test suite with high coverage. The experimental show that the proposed method generates a better test data than that of random test and Matlab/MBT test tool.

Keywords: embedded system, Matlab/simulink, MCDC coverage, testing, continuous signal

I. Introduction

1.1. Embedded model and testing problems

In this IoT century, embedded devices are playing more important role in several technological areas. In the embedded system development, it is common to use simulation for hardware design. The reason is that the hardware may not be available for testing, or may even not exist. Besides, the simulation can also avoid dangerous situations, such as equipment damage or human lack of safety. In most cases, testing is a feasible and reasonable method to guarantee the quality of practical models. This is because industrial models are very large and complex, and therefore formal verification takes very high cost, or is undecidable at the worst case. There are two main problems as follows.

Problem 1: Inputs of embedded systems are often time-continuous signals. The existing approaches to testing and verifying embedded models almost entirely focus on models with time discrete behavior, i.e., code generation models. These approaches generate discrete test inputs for embedded models with the goal of reaching runtime errors to reveal faults [3, 10], violating assertions inserted into the models based on some formal specification [8], and achieving high structural coverage [7]. Discrete test inputs, however, are seldom sufficient for testing embedded models, in particular, for those models with time-continuous behaviors.

Problem 2: Embedded system are complex. Embedded systems may have a high number of combinations of inputs and events, which can result in many different outputs. That means covering all possible runs in a manual testing activity is impossible. Thus, it is difficult to apply formal method or static analysis to generate the test data with high coverage. Moreover, the number of test data can be huge.

1.2. Proposed method

We propose a test data generation for time-continuous embedded system. To solve the first problem, each input signal is allowed to select any built-in signals in source blocks of Matlab/Simulink tool (e.g., sine, step signal…). Besides, we propose a method to modify Simulink model for testing purpose by modify Simulink model in order to allow each input can “select” one signal from a set of potential signals.

Next, to solve the second problem, we propose a system to automatically modify Simulink model and run simulation and check coverage.

1.3. Related works

There are several works about test data generation for embedded systems [1,2,3,4,5,6,7,8,9,12,13].

Matinnejad. et.al. (in [4, 5]) generated test data focus on time-continuous simulink model. The authors aim to design each input port a special signal based on search algorithm in order to maximize diversity among output signals. The method focuses on evaluating the relation between the change of output and input, does not
consider to check all possible runs of the models. Thus, it cannot be applied to test data generation with MC/DC coverage like our methods.

In [1], Godboley et.al generated test data for Simulink models with branch coverage. The method firstly generated C code for Simulink model, then applied a consolic testing tool for generated C program to obtain test suite with MC/DC coverage. The only one problem of this method is it cannot work well with big model because it applied a static analysis tool for generated C program. Thus, it is difficult to generate test data for practical models, which often have thousand of blocks. Our method uses testing technique, thus it can apply for hug models.

Tomita et.al [13] proposed a random test method in that each input signal is assigned for a signal template. Then, the a test data is instance of the signal template. We also use signal template for input signal. However, in this paper, we extend the idea by allow each input signal can use several built-in signal which allow input signal are more flexible.

II. Backgrounds

2.1. Simulink model

A Simulink model is constructed with various types of blocks, e.g., input/output, mathematical operator, logical/relation operator, (multiport) switch, and delay; blocks are connected with lines, transfer Boolean, integer or floating/fixed point data among them. Simulink supports hierarchical structure by subsystems with which a port may be equipped for selective activation/inactivation by external signals. Temporal behavior of a block is either based on continuous-time or discrete-time. Each model receipts the input from input blocks and returns the result in output blocks.

For example, Figure 1 is an embedded model for Modeling Clutch Lock-Up Using If Blocks. The clutch system in this example consists of two plates that transmit torque between the engine and transmission. There are two distinct modes of operation: (1) slipping - the two plates have differing angular velocities; (2) lockup - the two plates rotate together. In this model, the inputs are two From Work Space blocks (Engine Torque and Clutche Pedal); output are 6 outport blocks (we, wv, Locked Flag, Lockup Flag, Break-Apart Flag, FrictionTorque Required for Lockup); other blocks are if block, subsystem blocks (Friction model, Friction Mode Logic,…)

When testing Simulink models, we first build a test suite that consists of test data, which are groups of input signals, and then simulate and check behaviors of the model for the test criteria. Several test criteria are introduced to guarantee an acceptable quality, e.g., decision coverage, condition coverage, and modified condition/decision coverage (MC/DC coverage).

2.2. MC/DC coverage

It is typically required to test a model by using a high-coverage test suite. MC/DC originally defined in the standard DO-178B [1], intended to be an efficient coverage metric for the evaluation of the testing process of software incorporating decisions with complex Boolean expressions. The upcoming standard ISO 26262 [2] for safety-relevant automotive systems prescribes MC/DC for ASIL D as a highly recommended coverage metric. Actually, ISO 26262 (“Road vehicles – Functional safety”) requires to conduct an MC/DC coverage test.

MATLAB/Simulink has toolboxes for this purpose: Simulink Design Verifier6 (SLDV) and Simulink Verification and Validation7 (V&V).

MC/DC (modified condition/decision coverage) is a coverage criterion that requires all of the below during testing [1]:
- Each entry and exit point is invoked
- Each decision takes every possible outcome (DC)
- Each condition in a decision takes every possible outcome (MC)
- Each condition in a decision is shown to independently affect the outcome of the decision (MC/DC).

Independence of a condition is shown by proving that only one condition changes at a time.
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2.3. Test data of Simulink model

Definition 1 (Test data/Suite). A test data is a vector of input signals which assigned for each input port of Simulink model a signals. A test suite is a set of test data.

Given a test input, the model coverage is a measure of how exhaustively the model objects are exercised. The model coverage for a test suite is an accumulation of that of every test input in the test suite. In decision, condition and MC/DC coverage criteria, we need to consider block whose activity changes logical characteristics (i.e., data flow pattern) of the model. In the case of Simulink, they are, e.g., relational/logical operator blocks, (multi-port) switch blocks and subsystems with active-control ports.

For example, in Figure 1, a test data is a vector of two signals corresponding with pair of inputs (Engine Torque and Clutche Pedal). To obtain the coverage of if block, we have to create test data such that both conditions \((u_1 == 0)\), \((u_1 \neq 0)\) must happen sometimes.

2.4. Built-in signal as test data

A test data for Simulink model is characterized as a vector of input signals. Each signal may have an arbitrary shape of a waveform. However, input signals are provided by other electric modules which are likely well-controlled, or by physical objects which are dominated by physical laws. So it may be unnecessary to consider arbitrary signals. Additionally, considering well-controlled types of input signals (e.g., sine-wave, constant, step…), can be characterized with a few parameters, for achieving high decision, condition and MC/DC coverage. Besides, Simulink already provides a group of signals with such types. [13] also uses such built-in signal for randomly test data generation in Simulink models.

Therefore, we also use built-in input signals to design test data. To improve the coverage, the test data will use various of built-in signals for an input port instead of a single one.

III. Test Data Generation Method Using Built-In Signals

3.1 Proposed Model for testing

As mention in Subsection 2.4, built-in signals are used for input ports to easily control the parameters. Besides, we propose a method in that each test input will set input port a different built-in signal, not only a single one like [13]. By this, the test data are more varied. However, in Matlab/Simulink, a model \(M\), each input can only be connected with only one source block (stand for a built-in signal).

Figure 1: Modeling Clutch Lock-Up Using If Blocks [11]

Figure 2: Multiport Switch block

We have an observation that in Matlab/Simulink, the Multiport Switch block (Figure 2) determines which of several inputs to the block passes to the output. The first input is the control input and the remaining inputs are the data inputs. The value of the control input determines which data input passes to the output.
multiport switch can be used to automatically set any source block for an input port. For example, in Figure 3, if the input port \( \text{In1} = 1 \) the output of Multiport switch is repeating sequence signal; if \( \text{In1} = 2 \); the output of multiport switch is Sine wave signal; and if \( \text{In1} = 3 \), the output of multiport switch is Step signal.

![Figure 3: Multiport Switch block with 3 source blocks](image)

The modified Simulink model is called *model for testing*. The proposed method to obtain model for testing is shown in Algorithm 1.

**Algorithm 1: Generate model for testing**

Input:
- Original model \( M \) with list of input ports \( P = (p_1,\ldots,p_n) \)
- Set of possible signal blocks \( S = \{s_1,\ldots,s_k\} \)

Output: model for testing \( M_T \)

**begin**

For each input port \( p_i \)

If \( (p_i \text{ is continuous signal}) \) then

**begin**

Add Multiport switch \( m_i \) with source blocks \( s_1,\ldots,s_k \) as data input of multiport switch \( m_i \), control input is range from 1..\( k \);

Replace \( p_i \) by \( m_i \);

**end**;

End;

Thus, for model \( M \) and a test data \( (s_{i_1},\ldots,s_{i_n}) \), with \( s_{i_j} \in S \) (i.e., set of possible signal blocks). We now need not to manually modify \( M \) by connecting each input port \( p_i \) a source block \( s_{i_j} \). It can be automatically execute in Model for testing \( M_T \) by only setting the value of control input of multiport switch \( m_i \) to \( s_{i_j} \).

**Example 1:**

Original model in Figure 1 has two input ports, include: input \( p_1 \) is Engine torque, input \( p_2 \) is Clutch pedal. Assuming that, we set to each input port three types of signal: repeating sequence, sine wave, step. Thus, we can apply the multiport switch in Figure 3 with control input \( \in \{1,2,3\} \). The Model for testing is shown in Figure 4 with \( p_1 \) and \( p_2 \) are replace by \( m_1 \) (Multiport switch 1) and \( m_2 \) (Multiport switch 2). A test data \( (1,2) \) mean \( \text{in}_1 = 1 \), \( \text{in}_2 = 2 \), or \( p_1 \) is Repeating sequence signal and \( p_2 \) is Sine wave signal.
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3.2 Proposed test suite generation method

We next consider to select test input to obtain high coverage. The model for testing MT will be simulated with each input and evaluate the coverage.

Algorithm 2: GenerateTestsuite
Input: model for test MT
Output: test suite T
begin
Let ST is set of test data over MT;
Let T=∅
Let Coverage = (0,0,0);
for each t in ST
begin
simulation (MT,t);
tCoverage = checkMCDC();
if (Coverage < tCoverage)
begin
T = T {temp};
Coverage = tCoverage;
end;
endfor;
return T;
end;

In Algorithm 2, function simulation(MT,t) executes simulation of model MT with input setting for control inputs of multiport switches is t. Function checkMCDC() returns the coverage values of DC, CC, and MCDC when adding simulation with t. The Algorithm only selects the test data t into test suite T if the simulation MT with t increases the coverage.

Example 2: For model MT in Figure 4, we have ST is {(1,1), (1,2), (1,3), (2,1), (2,2), (2,3), (3,1), (3,2), (3,3)}.

IV. Experimental Result

We encode the proposed method using matlab mscript. Table 1 show the experimental result of MC/DC coverage with several Matlab/Simulink model using random test in [13] and the proposed method with set of source blocks are block Sine, Step, Random Number, Signal Generator (sawtooth), Pulse. The Model column shows the list of simulink models; Num of blocks column shows the number of blocks in the model; Num of Inputs shows the number of inputs in the model; %DC, %CC, %MCDC (Random) shows the coverage result of test data generation based on [13]; %DC, %CC, %MCDC (proposed method) shows the coverage result of
proposed methods. The experimental result of model in Figure 4 is shown in row 6th, corresponding with Model 6.

The experimental shows that the proposed method generate test suite with better MC/DC coverage, especially for the cases of big models with more than 400 blocks.

<p>| Table 1: MCDC COVERSAGES OF EMBEDDED MODELS |</p>
<table>
<thead>
<tr>
<th>STT</th>
<th>Model</th>
<th>#blocks</th>
<th>#Inputs</th>
<th>%DC,CC,MCDC (Random)</th>
<th>%DC,CC,MCDC (proposed method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model 1</td>
<td>66</td>
<td>4</td>
<td>dc = 11/12, cc = 0/0, mcdc = 0/0</td>
<td>dc = 11/12, cc = 0/0, mcdc = 0/0</td>
</tr>
<tr>
<td>2</td>
<td>Model 2</td>
<td>65</td>
<td>4</td>
<td>Fail</td>
<td>dc = 28/32, cc = 0/0, mcdc = 0/0</td>
</tr>
<tr>
<td>3</td>
<td>Model 3</td>
<td>63</td>
<td>4</td>
<td>dc = 0/0, cc = 2/2, mcdc = 0/0</td>
<td>dc = 0/0, cc = 2/2, mcdc = 0/0</td>
</tr>
<tr>
<td>4</td>
<td>Model 4</td>
<td>77</td>
<td>4</td>
<td>dc = 0/0, cc = 8/8, mcdc = 0/0</td>
<td>dc = 0/0, cc = 8/8, mcdc = 0/0</td>
</tr>
<tr>
<td>5</td>
<td>Model 5</td>
<td>69</td>
<td>4</td>
<td>dc = 0/0, cc = 8/8, mcdc = 0/0</td>
<td>dc = 0/0, cc = 8/8, mcdc = 0/0</td>
</tr>
<tr>
<td>6</td>
<td>Model 6</td>
<td>117</td>
<td>2</td>
<td>dc = 8/8, cc = 8/8, mcdc = 2/2</td>
<td>dc = 8/8, cc = 8/8, mcdc = 2/2</td>
</tr>
<tr>
<td>7</td>
<td>Model 7</td>
<td>501</td>
<td>4</td>
<td>dc = 93/129, cc = 46/64, mcdc = 4/13</td>
<td>dc = 126/129, cc = 64/64, mcdc = 11/13</td>
</tr>
<tr>
<td>8</td>
<td>Model 8</td>
<td>485</td>
<td>2</td>
<td>dc = 122/129, cc = 64/64, mcdc = 13/13</td>
<td>dc = 125/129, cc = 64/64, mcdc = 13/13</td>
</tr>
<tr>
<td>9</td>
<td>Model 9</td>
<td>507</td>
<td>4</td>
<td>dc = 93/129, cc = 46/64, mcdc = 4/13</td>
<td>dc = 123/129, cc = 64/64, mcdc = 13/13</td>
</tr>
</tbody>
</table>

V. Conclusion

The paper presented a method to automatically generate test data for embedded model with time-continuous input. Instead of generating test data as arbitrary signals, the built-in signals (e.g., sine-wave, step-wave, …) are used. Besides, we improve the original embedded model by applying Algorithm 1. Then, the test data for embedded model can be generated and executed automatically. Algorithm 2 supports selection and evaluation of the MCDC coverage. The experimental result shown that the proposed method generates test data for time-continuous embedded system with higher coverage than random testing.

For future work, we plan to apply testing techniques and static analysis to generate testcases for embedded model with huge number of inputs.

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References
