Increasing Usability of Spin-based C Code Verification Using a Harness Definition Language

Leveraging Model-driven Code Checking to Practitioners

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ABSTRACT

Due to its capabilities to integrate well with C code, Spin has been used for C code verification based on environment models that describe the context, in which the software under verification is expected to run. In practice this approach requires an in-depth knowledge of Promela and the underlying technology. Moreover environment models tend to be verbose and exhibit heavily intertwined statements of Promela and C code. Thereby, writing and understanding such hybrid models is difficult and error-prone. Alleviating this problem we develop a specialized language for expressing environment models used in verification harnesses. Our language harmonizes the use of Promela and C in a homogeneous way that is suitable for practitioners. We show how a small number of language concepts is sufficient to define environments for a wide variety of commonly encountered software components written in C. The approach is integrated in the development platform mbeddr, a technology stack for embedded programming and formal verification developed on top of JetBrains' MPS language workbench.

Categories and Subject Descriptors

D.2.4 [**Software/Program Verification**]: Model Checking; D.2.5 [**Software and its engineering**]: Software testing and debugging

Keywords

Spin, domain-specific languages, model checking, testing

1. INTRODUCTION

Formal verification increases the quality of software by enabling the developers to discover subtle bugs. Despite dramatic improvements of the verification algorithms and tooling in the last 10 years, software verification tools are regarded as expert tools and developers shy away in front of their (perceived) complexity.

While software verification is conventionally applied on the source code of the *Software Under Verification* (SUV), an alternative approach based on Spin, a highly mature explicit state model-checker, has been proposed in [11]. In this scenario, a Promela model is not created from the SUV directly, but from its environment, which the SUV interacts with. Taking advantage of the possibility to embed C code in Promela, Spin generates a verifier that systematically explores the states of the environment model and calls the SUV in the different states of this model. A prerequisite of this approach is that calls to the SUV are atomic, i.e. there are no intermediate states in the environment model between the call and the return. For this reason, the approach is best applicable in the context of unit testing, treating the SUV as a black-box. The approach is therefore complementary to white-box testing approaches such as KLEE [4] that generate tests from the source code of the SUV with the purpose of maximising code coverage during test execution.

The environment-driven approach to code checking draws its advantage from the fact that the SUV is called in the context of its usage—provided the environment model faithfully expresses this usage. The developer has a full range of possibilities at hand: from a trivial model with a single state and no constraints on the SUV input data (the most general model) to a highly elaborated state model with constraint data sets. This way the developer can control the extend to which the SUV is analysed at runtime.

Deploying Spin for the exploration of the environment model requires, naturally, the use of Promela as its specification language. C code developers who are not trained in formal verification find it hard to apply Promela with its specific verification features for this purpose, rendering this approach quickly unacceptable for them. In a long-term pursuit, Siemens invests into technologies to make formal verification techniques usable up to a level that practitioners can benefit from its potential. The approach outlined in this paper is based on language engineering technologies to hide the complexity of using formal methods directly [15, 14]. The entire approach is implemented in mbeddr [19][1], an integrated development environment (IDE) and open source stack of domain specific languages on top of C to assist the development of safety-critical C code.

[1] www.mbeddr.com

```
1  c_decl { uchar my_array[4], *res; }
2
3  active proctype sort_harness() {
4    byte elem0, elem1, elem2, elem3;
5    select(elem0 : 0 .. 255);
6    ...
7    select(elem3 : 0 .. 255);
8    c_code {
9      my_array[0] = Psort_harness->elem0;
10     ...
11     my_array[3] = Psort_harness->elem3;
12     res = sort(my_array, 4);
13     for(i = 0; i < 3; i++) {
14       if (!(res[i] <= res[i+1])) {
15         uerror("...");
16 } } } }
```

```
1  decls { uchar my_array[4], *res; }
2
3  harness sort {
4
5    nondet_assign(my_array, 0, 255);
6
7
8
9
10
11
12   res = sort(my_array, 4);
13   for(i = 0; i < 3; i++) {
14     assert(res[i] <= res[i+1]);
15   }
16 }
```

Figure 1: Verification harness definition using Promela (left) and a proposed higher-level DSL (right)

To outline our language engineering approach, consider Figure 1 that sketches the approach of environment-driven code checking using a sorting algorithm called `sort()` as the SUV. The environment model, called *verification harness* in the remainder of the text, `sort_harness()` is provided as a Promela model (left-hand side). The model is conceptually simple. It generates valid input data through a nondeterministic assignment of values to the array to be sorted (lines 4-11), calls the `sort()` function (line 12) and checks that the array returned is correctly sorted (lines 13-16). Note the mixed usage of Promela statements and embedded C code statements. The right-hand side illustrates our proposed domain-specific language (DSL) which hides the repetitive parts in the Promela model and offers a simple and direct way to describe the verification harness by blending the distinction between C code and Promela statements.

The work presented in this paper enhances the model-driven code checking approach [11] with the following aspects: 1) We define a small set of concepts of a harness definition language which are conceptually simple to use, yet powerful enough to support the verification of a wide variety of SUVs; 2) We show how these constructs are encoded in Promela to derive executable environment models that are further processed by Spin; 3) We develop an enhanced way to express witnesses of failed verification runs to ease their understanding, and 4) We describe mbeddr-spin, a tool that implements our approach.

The remainder of the paper is organized as follows. In Section 2 we describe a set of pragmatic reasons for using Spin for verifying C code via environment models and the challenges that need to be overcome. Section 3 provides an overview over MPS and mbeddr, the technological base used to implement our approach. Section 4 presents our verification harness definition language with a set of needed language concepts and their translation into Promela. In Section 5 we describe how our approach can be instantiated to verify various categories of SUVs that are often encountered in practice. Section 6 provides a discussion about the approach and results obtained so far, while Section 7 reviews the known body of related work. Section 8 concludes the paper and sketches directions for future work.

2. SPIN FOR C CODE VERIFICATION

We review the advantages and usability challenges of using Spin for an environment-driven approach to C code verification and proposes solutions to overcome theses challenges.

2.1 Advantages of Spin

Despite big improvements of software verifiers in the last decade [2], there is a set of pragmatic reasons which make the use of Spin for code verification appealing when compared to specialized software model checkers.

Language subset of C/C++. To our knowledge, existing software model checkers work only with subsets of the C/C++ language. That is, compiler specific extensions, assembler fragments or complex features of C/C++ are not supported. In contrast, Spin can be used to verify every code that can be compiled.

Use of libraries. When the SUV uses libraries, software model checkers require to model the observable behaviour of these libraries as well. However, precise modelling is many times impossible (or impracticable) and thereby the analyses results are imprecise. Environment-driven code checking with Spin does not suffer from this drawback because it generates a verifier that contains the code of the SUV together with any libraries used in binary form.

Code that defies verification. There are cornerstone cases where C code model checkers have difficulties in analysing the code, e.g. when using floating-point numbers or deep and complex loops. In many of these cases environment-driven code checking offers an alternative because regions of the input space can be exhaustively verified, provided the execution of SUV is fast enough.

Combining testing with model checking. As described in [8] Spin allows to blend exhaustive model checking with testing, e.g. by generating some explicit input data randomly in a deliberate manner when exhaustive model checking over the whole range of input data is not feasible.

Semantic misalignments. There is always a possibility of semantic misalignments of interpreting the code between the C compiler and the model checker. This is true especially when the code contains fragments which are not specified by the C standard. Due to the fact that Spin verifies the binary code, these misalignments cannot happen.

2.2 Usability Challenges

The reasons cited above are our main motivation to enhance the mbeddr platform with support for environment-driven code checking using Spin. Nevertheless the approach still poses challenges in its applicability to practitioners due to the following reasons.

Modelling of the verification harness. Developers are required to have a deep understanding of Promela and its idioms. Small mistakes in the specification of the environment spans, for example, a smaller state space than expected reducing its usefulness. Furthermore, descriptions of relatively simple environments tend to be verbose. Developers simply shy away in front of this (perceived) complexity.

Lack of IDE support. We are currently not aware of IDEs that enable the definition of Promela models and their integration with C code of the SUV. Without IDE support, most of the code checking work must be done manually, e.g. building the verifier.

Tracking the SUV state. If the SUV has internal state, it must be tracked in the environment model such that the observed SUV behaviour becomes deterministic and verification results repeatable. Otherwise Spin looses control over the SUV and it cannot faithfully decide about a failure (both, false positives and false negatives, are possible).

Understanding counterexamples. The error trail generated by Spin in case of a failure is—especially when C code is embedded in the Promela model—verbose and hard to understand. Additional lifting mechanisms are therefore required that relate the steps of the error trail to the statements in the verification harness.

2.3 Tackling the Challenges

In order to address these challenges we are specifying environment models in a higher-level description language that deals with the peculiarities of verification harnesses and supports practitioners. The design of this language is driven by the following goals:

G1) **Simple syntax for harness definition**: The syntax must be simple and based on a few high-level constructs to ease learning the new language. In addition, the constructs must be also sufficiently expressive such that a wide variety of C components can be verified. It should "feel like" C and serve both beginners and advanced users equally.

G2) **Support for understanding the witness**: The error trail generated by Spin shall be enriched with additional information about the SUV state such that comprehension of the counterexample is easier. This goal implies also that the error trail is provided in a format which can be parsed and displayed in an easy-to-understand manner.

3. MPS AND MBEDDR

In the following we give a brief overview of the technological basis provided by the language workbench MPS and its instantiation for embedded C code development mbeddr. Afterwards we discuss the integration of Spin into this technology stack.

3.1 JetBrain's Meta-Programming System

Our work relies on language engineering technologies, which refer to defining, extending and composing programming and domain-specific languages (DSLs) and their integrated development environments (IDEs). Language workbenches are tools that support efficient language engineering. The language workbench MPS[2] supports all aspects of the definition of DSLs such as abstract syntax, advanced editors, type systems, code generators and analysers. It serves as the core technology for our implementation.

3.2 MBEDDR

The tool mbeddr is an open source technology stack for embedded C code development and verification. It provides incremental, modular and domain-specific extensions of C implemented on top of MPS. Figure 2 shows an overview over the mbeddr architecture [19]. In a nutshell, mbeddr offers support for three concerns in the development of embedded systems: the *implementation concern* contains engineering features to support the generation of executable code; the *analysis concern* contains features that enable code analysers and integrated test tools; and the *process concern* (not presented in the figure for brevity reasons) offers support for the development process and software lifecycle such as the definition of requirements.

The work presented in this paper is an extension of mbeddr's analysis concern. The analysis concern integrates different external analysis tools. Besides the integration of a tool per se, the analysis concern offers DSLs for defining verification harnesses, which are verification tool specific. At higher levels, mbeddr users have the possibility to use the ANSI-C specification language (ACSL [1]) for defining contracts on functions—from the ACSL contracts users can generate C code assertions or specialized C comments that tools like Frama-C can consume. Another possibility is to express more complex verification conditions through property patterns that are translated into C snippets containing assertions. Different high-level abstractions come with their specific analyses, e.g. checks for completeness and consistency of decision tables [16]. The most advanced integration is that of CBMC [5]. The integration of further tools are at different stages of maturity and we are continuously experimenting with different verification technologies to enhance mbeddr's analysis capabilities.

[2] https://www.jetbrains.com/mps/

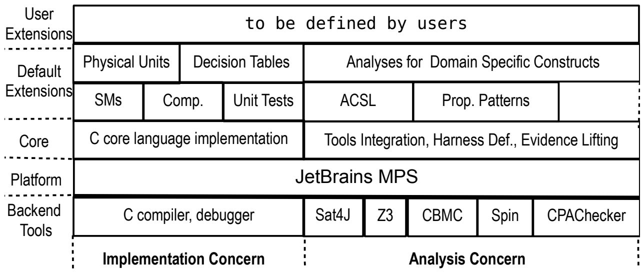


Figure 2: Overview over the technology stack of mbeddr; DSLs for coding (left-hand side), tools and DSLs for formal analyses (center).

3.3 Integrating Spin into MBEDDR

Language Definition. This paper comprises the definition of a DSL for the design of verification harnesses, which starts with the design of the the language concepts and their relationships between them (abstract syntax). Figure 3 shows a high-level overview of how the Promela language implementation and its integration with other languages are supported in mbeddr. A PromelaModule contains entities of type IPromelaModuleContent that can be, for example, CDecl or ProcType statements. A CDecl statement contains top level elements of mbeddr's IModuleContent that enables the use of any language supported in mbeddr, the C language in our case, to be used inside a Promela CDecl statement. As an extension of the Promela language, we have defined the high-level harness DSL (Figure 3-bottom) as described in Section 4.

Generator and Build Process. Deploying features from the underlying MPS platform, we can generate text such that it can be passed to compilers or any other tools. The way forward to implement the Promela model generator for the verification harness description is to provide a model-to-model transformation from the DSL for harness definition into the Promela language first. Then concrete code is generated from the Promela model (model-to-text transformation).

Once text is obtained, MPS allows the definition of build steps which contain the calling of Spin and GCC to compile the verifier pan. Once the pan executable is built, it is executed in a background process. If the verification fails, the produced error trail is read and the witness is fed back to mbeddr and displayed in its UI (see Figure 15-right).

4. HARNESS DEFINITION LANGUAGE

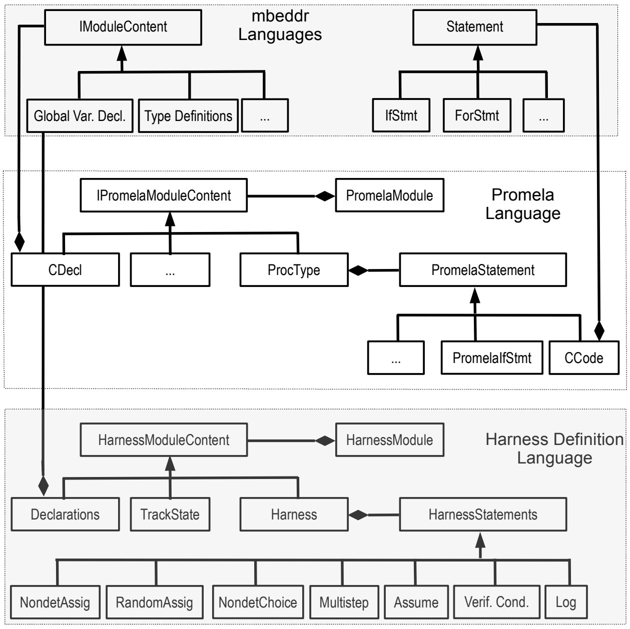


Figure 3: Overview of the language composition between mbeddr, Promela and the language for harness definition.

We develop several high-level concepts of a harness definition language to enable a convenient definition of a verification harness. For each concept its rationale and its translation rules to Promela are described. Our aim is to make the harness look like C code with a minimal number of special constructs in order to lower the acceptance hurdle for developers who are the targeted users of the approach. The language concepts are introduced "by example" to ease readability.

Harness Module Concept. A harness definition describing the environment, in which the SUV is executed, is realized in the *harness module* concept. It comprises the following four sections: 1) Import of C headers that describe the interface of the SUV used in the harness logic; 2) Declaration of input data used when calling the SUV from the harness; 3) Tracking of SUV state variables (optional); and 4) Specification of the harness logic, including assertions.

Figure 4 presents a harness skeleton and its encoding in Promela. The import section (line 1) contains a header file that describes the interface of the SUV. A variable declaration of an array of type tpe_t appears in line 3. Such declarations are later transformed to Promela c_decl statements in the build process. The next line contains the information about a tracked variable; this will be automatically translated into a c_track statement including information about the variable size. All tracked variables are *UnMatched* and they do not go into the state vector. The harness logic is given in line 6. It carries a name and a body that contains the scenario of the call to the SUV which is detailed in further language concepts below.

```
1  imports "suv.h"
2
3  decls { tpe_t[5] arr; }
4  track state: arr
5
6  harness logic_definition() { /* code */ }
```

```
1  c_decl {
2    \#include "suv.h"
3    tpe_t[5] arr;
4  }
5
6  c_track "&arr" "5*sizeof(tpe_t)" "UnMatched"
7
8  active proctype logic_definition() {
9    /* code */ skip
10 }
```

Figure 4: Encoding of the harness module.

Logging Concept. When an assertion fails, Spin prints a witness that contains the path taken through the Promela model of the verification harness and the values of its variables. Promela offers the Printf construct to print additional information. We leverage this functionality and generate automatically Printf statements from all constructs that assign values non-deterministically or randomly. Furthermore, we allow users to log additional information in order to improve the readability of a witness. In order to recognize these statements later in the error trail, we use a special format for the strings printed—all strings denoting key/value pairs are prefixed with ###. Thereby we obtain a lifted witness representing a filtered error trail and presenting the relevant information to understand the failure at the harness level (see Figure 15).

```
decls { int8_t var; }

harness logic_definition() {
  //code 1
  log witness(var);
  //code 2
}
```

```
c_decl { int8_t var; }

active proctype logic_definition() {
  //code 1
  c_code { Printf("### var=%d\n", var); }
  //code 2
}
```

Figure 5: Logging information in the witness.

Non-deterministic Assignment Concept. The `nondet_assign` statement assigns non-deterministically a value from a given range to a variable. The variables can have different types and the statement is adequately encoded into Promela depending on the type. The non-deterministic assignment concept is an extension of the `select` statement in Promela by dealing automatically with more data types (e.g. arrays with a constant size, enumerations) and ranges (e.g. ranges with discrete values). Furthermore and as discussed before, a `Printf` statement is added after each variable assignment to display the chosen value in a witness. Figure 6 illustrates this concept. While the value is non-deterministically assigned to the given variable, the backtracking feature of the model checker ensures that eventually all possible values are tried. Figure 7 shows the case when the variable is of an enumeration type, which is translated to Promela's `select` statement.

```
1  decls { char ch; }
2
3  harness p() {
4    // code 1
5    nondet_assign(ch, {'a', '.', '\'});
6    // code 2
7  }
```

```
1  c_decl { char ch; }
2
3  active proctype p() {
4    // code 1
5    byte tmp__ch;
6    if
7      :: tmp__ch = 'a';
8      :: tmp__ch = '.';
9      :: tmp__ch = '\\';
10   fi;
11   c_code {
12     ch = Pp->tmp__ch;
13     Printf("### ch = %c", ch);
14   }
15   // code 2
16 }
```

Figure 6: Encoding of nondet_assign where the domain is a set of discrete elements of type char. Besides the variable assignment itself, line 13 contains an automatically inserted Printf statement in the special witness format.

```
decls {
  enum EN {
    FIRST = 10, SECOND = 20, THIRD = 30
  } en;
}

harness p() {
  // code 1
  nondet_assign(en);
  // code 2
}
```

```
c_decl {
  enum EN {
    FIRST = 10, SECOND = 20, THIRD = 30
  } en;
}

active proctype p() {
  // code 1
  int en_idx;
  select(en_idx : 0 .. 2);
  c_code {
    if (Pp->en_idx == 0) {
      en = FIRST;
      Printf("### en = FIRST");
    }
    ...
  }
  // code 2
}
```

Figure 7: Encoding of nondet_assign for variables of an enumeration type.

Random Assignment Concept. In many practical cases the range of input values to the SUV is too big to be explored in an exhaustive manner. To deal with this situation the `random_assign` statement in the harness language assigns a given number of random values to a variable according to the range description and a certain seed value—an approach presented originally in [8]. The seed value enables the replay of the verification run. Again, the random assignment concept is able to deal with variables of different types, see Figure 8.

Assumption Concept. Frequently the requirements for the SUV specify assumptions about the environment in form of constraints between valid inputs to the SUV. A proper environment definition thereby should enforce that the required constraints between inputs hold in order for them to be valid. For specifying such constraints, we define the `assume` statement that takes a Boolean expression representing the assumption. The assumption must hold for subsequent statements to be executed. If the assumption does not hold, then the execution is broken, a backtracking step is performed and the exploration continues after this reached state. Figure 9 illustrates the concept and its translation to Promela as a `goto` statement to a label automatically inserted at the end of the harness code.

```
decls { long v; }

harness p() {
  // code 1
  random_assign(v, [200, 300], 2, 50);
  // code 2
}
```

```
c_decl { long var; }

active proctype p() {
  // code 1
  bool rndInit = false;
  int cnt = 0;
  if
    :: !rndInit ->
        rndInit = true;
        c_code { srand(2); }
    :: else -> skip;
  fi;
  do
    :: cnt < 50 -> cnt = cnt + 1;
    :: break;
  od;
  c_code {
    var = (rand() % (300 - 200)) + 200;
    Printf("### var = %d", var);
  }
  // code 2
}
```

Figure 8: Encoding of random_assign.

```
harness p()
{
  // code 1
  assume(cond);
  // code 2
}
```

```
active proctype p() {
  // code 1
  if
    :: !cond -> goto end_label;
    :: else -> skip;
  fi;
  // code 2
end_label: skip;
}
```

Figure 9: Encoding of assume. If the assumed condition does not hold, we jump to the end of the process and force a backtracking step.

Non-deterministic Choice Concept. A possibility needs to be provided to select the next behaviour of the harness logic to be executed in a non-deterministic manner. We support this via the `nondet_choice` construct which provides multiple guarded behaviours. A choice succeeds if the guard of the selected behaviour is true. When none of the guards evaluate to true, then a default branch that must be always present is executed, see Figure 10.

```
harness p()
{
  // code 1
  nondet_choice {
    choice: guard1 -> { /* code1 */ }
    choice: guard2 -> { /* code2 */ }
    default: { /* code3 */ }
  }
  // code 2
}
```

```
active proctype p() {
  // code 1
  if
    :: guard1 -> { /* code1 */ }
    :: guard2 -> { /* code2 */ }
    :: else ->   { /* code3 */ }
  fi;
  // code 2
}
```

Figure 10: Encoding of nondet_choice.

```
harness p()
{
 // init
 multistep(N) {
  // body
 }
}
```

```
 1  active proctype p() {
 2    // init
 3    int __crtStep=0;
 4    // step 1
 5    {
 6      __crtStep = __crtStep + 1;
 7      c_code {
 8        Printf("### Iteration = %d\n",
 9          __crtStep);
10      }
11      // body
12    }
13    // ... (N - 1) times
14  }
```

Figure 11: Encoding of multistep by copying the body N times; also witness information about the current state is printed (line 8).

Multi-Step Verification Concept. When the SUV exhibits internal state we need multi-step verification. It assumes that the SUV is called in a loop with different input values for each call. To facilitate this behaviour in the harness definition, we define the `multistep` statement that is translated in Promela by copying the body N times. The iteration number is logged to ease the understanding of the witness. See Section 5.3 for a concrete application.

Further Concepts. Besides the concepts listed above, the harness definition language offers additional features such as calling the SUV inside the harness, variable assignments, loops, and assertions. The translation of these concepts into Promela is straightforward. Whenever the generator from the harness definition language into Promela encounters references to C code, or C statements, it wraps them automatically with proper `c_code` or `c_expr` expressions.

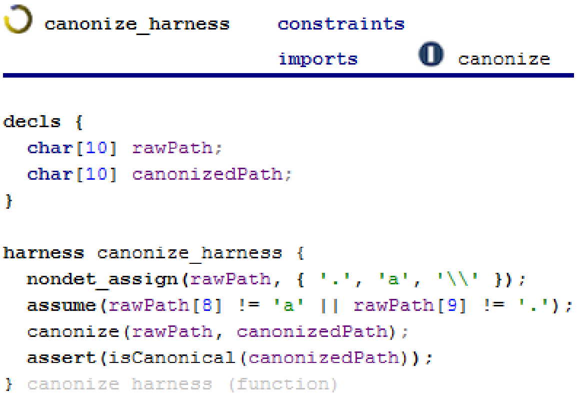
5. COVERED SUV CATEGORIES

Now we present typical categories of SUVs that are covered by the environment-driven code verification approach. Each of the sub-sections from below deals with one category and demonstrates how the verification harness can be modelled using the language defined in the previous section.

5.1 Cat I: Side-Effects Free Function

This category covers the case when the SUV is represented by a function that is side-effects free, i.e. its output depends solely on the provided input data. In addition the sets of input and output parameters are distinct. In this case, the harness is composed of variable declarations for inputs and outputs of the SUV and the main harness logic. Typically the harness logic produces input values to the SUV non-deterministically and filters the valid values using the `assume` statement. SUV outputs, i.e. return values, are compared in `assert` statements with expected values provided differently.

In Figure 12 an example of a harness is presented that verifys the function `canonize()` for path names, which is similar to the one presented in [11]). The harness generates all possible strings of length 10 that contain '.', 'a' or '\', but do not end with the suffix "a.".



```
canonize_harness        constraints
                        imports      canonize

decls {
  char[10] rawPath;
  char[10] canonizedPath;
}

harness canonize_harness {
  nondet_assign(rawPath, { '.', 'a', '\\' });
  assume(rawPath[8] != 'a' || rawPath[9] != '.');
  canonize(rawPath, canonizedPath);
  assert(isCanonical(canonizedPath));
} canonize harness (function)
```

Figure 12: Example of harness definition for verifying a side-effects free function.

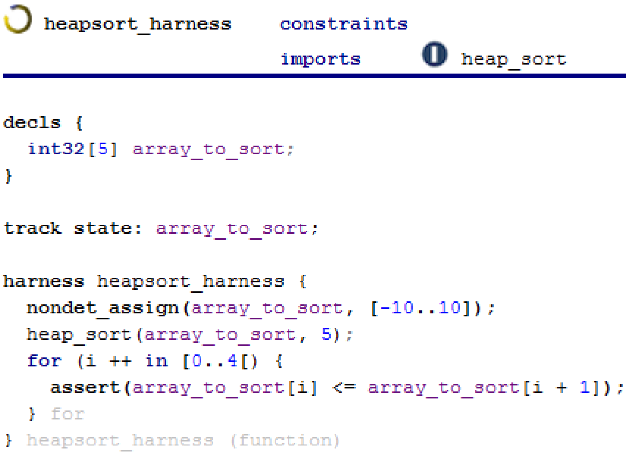
5.2 Cat II: In/Out Parameters

This category describes cases when the SUV interface is represented by a side-effects free function, which possesses some parameters that are used both as inputs and as outputs. Additionally to the harness definition for category I, the harness must track the variable which is used as an actual in/out parameter in the call of the function.

Figure 13 presents an example of such a harness that verifies a sorting algorithm `heap_sort`. Sorting of elements provided in an array occurs in place. At first, an array with five elements is non-deterministically initialized with values between -10 and 10; then the sorting function is called; and the returned array is checked for correctness of the function. The state of the array that serves as in/out parameter must be tracked such that, when backtracking is performed, the search algorithm can continue from the last state stored in this array. In this example, backtracking happens each time after an assignment to the array was processed and the SUV is called again with the next assignment.

5.3 Cat III: State-based Verification

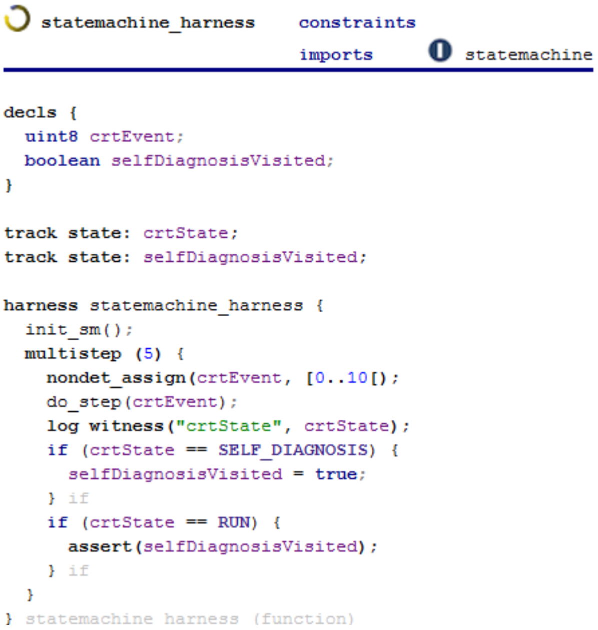
Another category exists when the SUV contains internal state and its behaviour depends on this state. An example for this category are implementations of state machines. They are typically implemented through a stepper function that processes its in parameter as input event to trigger the execution of the state machine.



```
heapsort_harness        constraints
                        imports      heap_sort

decls {
  int32[5] array_to_sort;
}

track state: array_to_sort;

harness heapsort_harness {
  nondet_assign(array_to_sort, [-10..10]);
  heap_sort(array_to_sort, 5);
  for (i ++ in [0..4[) {
    assert(array_to_sort[i] <= array_to_sort[i + 1]);
  } for
} heapsort_harness (function)
```

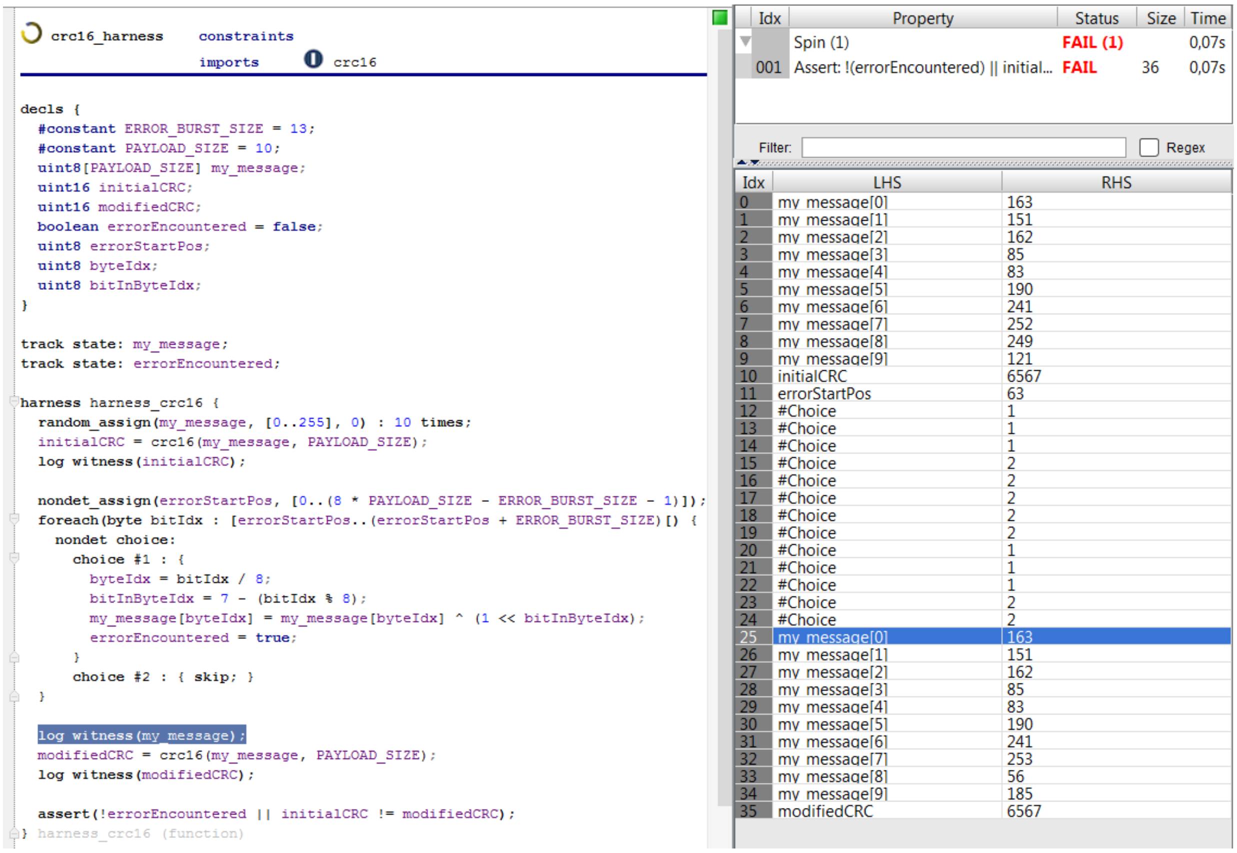
Figure 13: Example of a harness definition for verifying a function with in/out parameters.

In Figure 14 an example of a harness for state machine verification is presented that makes use of the multi-step verification. The SUV contains the `init_sm()` function for initializing the state machine and the `do_step()` function for stepping through. Because the harness needs to reason about the correct state after each step, all variables related to the SUV state must be tracked in the harness. The `multistep` statement ensures the continued execution of the



```
statemachine_harness        constraints
                            imports      statemachine

decls {
  uint8 crtEvent;
  boolean selfDiagnosisVisited;
}

track state: crtState;
track state: selfDiagnosisVisited;

harness statemachine_harness {
  init_sm();
  multistep (5) {
    nondet_assign(crtEvent, [0..10[);
    do_step(crtEvent);
    log witness("crtState", crtState);
    if (crtState == SELF_DIAGNOSIS) {
      selfDiagnosisVisited = true;
    } if
    if (crtState == RUN) {
      assert(selfDiagnosisVisited);
    } if
  }
} statemachine harness (function)
```

Figure 14: Example of a harness definition for verifying a state machine.



```
crc16_harness    constraints
                 imports      crc16

decls {
  #constant ERROR_BURST_SIZE = 13;
  #constant PAYLOAD_SIZE = 10;
  uint8[PAYLOAD_SIZE] my_message;
  uint16 initialCRC;
  uint16 modifiedCRC;
  boolean errorEncountered = false;
  uint8 errorStartPos;
  uint8 byteIdx;
  uint8 bitInByteIdx;
}

track state: my_message;
track state: errorEncountered;

harness harness_crc16 {
  random_assign(my_message, [0..255], 0) : 10 times;
  initialCRC = crc16(my_message, PAYLOAD_SIZE);
  log witness(initialCRC);

  nondet_assign(errorStartPos, [0..(8 * PAYLOAD_SIZE - ERROR_BURST_SIZE - 1)]);
  foreach(byte bitIdx : [errorStartPos..(errorStartPos + ERROR_BURST_SIZE)[) {
    nondet choice:
      choice #1 : {
        byteIdx = bitIdx / 8;
        bitInByteIdx = 7 - (bitIdx % 8);
        my_message[byteIdx] = my_message[byteIdx] ^ (1 << bitInByteIdx);
        errorEncountered = true;
      }
      choice #2 : { skip; }
  }

  log witness(my_message);
  modifiedCRC = crc16(my_message, PAYLOAD_SIZE);
  log witness(modifiedCRC);

  assert(!errorEncountered || initialCRC != modifiedCRC);
} harness_crc16 (function)
```

Idx	Property	Status	Size	Time
	Spin (1)	FAIL (1)		0,07s
001	Assert: !(errorEncountered) || initial...	FAIL	36	0,07s

Filter: □ Regex

Idx	LHS	RHS
0	my_message[0]	163
1	my_message[1]	151
2	my_message[2]	162
3	my_message[3]	85
4	my_message[4]	83
5	my_message[5]	190
6	my_message[6]	241
7	my_message[7]	252
8	my_message[8]	249
9	my_message[9]	121
10	initialCRC	6567
11	errorStartPos	63
12	#Choice	1
13	#Choice	1
14	#Choice	1
15	#Choice	2
16	#Choice	2
17	#Choice	2
18	#Choice	2
19	#Choice	2
20	#Choice	1
21	#Choice	1
22	#Choice	1
23	#Choice	2
24	#Choice	2
25	my_message[0]	163
26	my_message[1]	151
27	my_message[2]	162
28	my_message[3]	85
29	my_message[4]	83
30	my_message[5]	190
31	my_message[6]	241
32	my_message[7]	253
33	my_message[8]	56
34	my_message[9]	185
35	modifiedCRC	6567

Figure 15: Harness definition for checking a CRC-16 algorithm (left) and the presentation of a witness (right). A double-click on a witness entry selects the corresponding node in the harness definition. Additional logging of harness variables is taken in the witness and facilitates its understanding.

state machine for the given number of steps.

5.4 Cat IV: Huge Input Spaces

We often encounter situations when the oracle has a complex structure and cannot be captured through simple assertions or temporal logic patterns. An example system for this category is a Cyclic Redundancy Check (CRC) error-detection algorithm. Such algorithms might exhibit subtle defects (e.g. when a "bad" polynomial is used) or their implementation might be simply faulty. Testing CRC algorithms is difficult because of the huge input space caused by the multitude of possible messages and the occurrence of error bursts. In order to tackle the complexity of the input space, it is sensible to combine random testing with exhaustive verification. Parameters with an input space that is too large to be systematically explored are subjected to a random selection of values, while for the other input parameters exhaustive verification is applied.

In Figure 15-left a harness is presented for checking an implementation of the CRC-16 algorithm. The payload of a message is initialized randomly (in our example 10 bytes in the array `my_message`) for 10 times. That is, 10 different, randomly chosen payloads are generated and submitted to the SUV which calculates the CRC-16 value. Finally, all possible burst errors up to length 13 are applied on the message at any location inside the payload. A chosen error burst is either applied or skipped; see the `nondet_choice` statement. The CRC-16 value for the disturbed payload is computed again. It is expected that the CRC-values for the original payload and the disturbed one are different under all considered cases, which is formulated in the corresponding `assert` statement. The `log witness` statements serve as additional information in generated counterexamples.

Figure 15-right presents a witness returned by Spin and lifted in mbeddr. Due to the special format of the logging construct, the tool mbeddr-spin can establish the relation between the witness entry and the corresponding statement in the verification harness. By double-clicking on an entry of the witness, the corresponding harness part, from which that witness entry originates, will be selected in the editor. The link between the witness and the editor makes it easier to understand big witnesses and navigate through the harness code.

6. DISCUSSION

The approach introduced in Sections 4 and 5 led to the development of the tool mbeddr-spin that extends the feature set of the mbeddr platform. It targets specifically the development of safety-critical embedded C code. In this application domain, environment-driven code verification has its advantage because it avoids any semantic misinterpretations of code between the compiler and the model checker that could render results obtained from direct C code verification useless (see Section 2). The mbeddr-spin tool is currently in its prototype stage where we conduct experiments with C code implementations from a number of industrial projects to evaluate its usefulness. The evaluation covers (1) the applicability of the tool and (2) its usability as observed by users. First results are reported below.

6.1 On Practical Applicability

The use of Spin as the underlying model checker proofs beneficial due to its maturity. Environment models for SUVs at unit test level tend to describe little behaviour and posses complexity rather in the definition of the input data domain. Runtime performance of the pan executable is mostly constraint by the execution time of a called C function of the SUV. Though, performing myriad calls of the SUV quickly exhausts the available time resources. The total number of SUV calls needs to be controlled therefore by the user. Consider the verification of the CRC-16 algorithm (Figure 15). The verification harness applies 10 different payloads, each 10 bytes long. The generation of mutated payloads with error bursts up to length 13 produces $(8{*}10{-}13){*}2^{13} = 548864$ modified payloads. On modern machines Spin is able to cover this amount of data in a few seconds.

A limitation of the approach applies when verifying state-based SUVs whose state variables are (partly) not accessible (e.g. when the SUV uses a library that has internal state). In this case the backtracking functionality of Spin cannot be used because the state of the SUV cannot be backtracked. One could rely on the availability of a reset function of the SUV that brings it back to its initial state. This assumption is frequently exploited in testing. However when applying a SUV reset for backtracking a modified state exploration strategy inside the model checker is required: When backtracking, the model checker re-starts from the initial state of the model and performs the (shortest) path to reach the backtracked state, from where it chooses another execution path of the model and, hence, in the SUV.

6.2 Revisiting design goals G1 and G2

We conducted the work in order to support developers in the application of formal methods by hiding them under the hood of a proper language and IDE. The use of a DSLs stack such as mbeddr is very helpful in this respect. It allows the extension of the IDE that the engineer already knows with additional features. For example, syntax highlighting and auto-completion are provided out of the box for the newly designed harness definition language. Such usability features make the application of a new language easy and less laborious as well as attractive and motivating to learn.

Moreover, we succeeded in the design of a homogeneous language that gets rid of the intertwined usage of Promela and C code (goal **G1**). The offered language concepts for harness definitions are at a higher level of abstraction than Promela such that a common language integrating both Promela and C could be defined.

Deploying the analysis aspect of mbeddr we were able to implement debugging support based on the witness filtered from a Spin error trail (goal **G2**). The user only sees entries in the witness that have a direct correspondence to statements in his verification harness. Details from the underlying Promela model are hidden to him. This way, the user can click on an entry from the witness and the corresponding harness code is highlighted (see Figure 15).

7. RELATED WORK

The paper [12, 11] introduces the concept of model-driven code verification using Spin. In this approach, a Promela model represents the environment, in which the code to be verified is embedded and which guide the verification process. The work in [8] presents a unified framework that uses Promela both for test harness definition and model checking. Our work directly builds on these approaches and extends them by defining a higher-level harness definition language that captures commonly encountered patterns of harness definitions. Moreover, we deeply integrate Spin in the mbeddr development environment and thereby offer the same IDE for writing C code and and harness definitions using the new language. For this reason the whole approach becomes easier to understand and use by software developers from practice. Furthermore, advanced users can write complex harnesses easier.

The paper [18] presents an approach that uses Spin to check the C code generated from a high-level DSL for describing rules. The verification harness is automatically generated and the verification result and witness is lifted at the level of the DSL. Compared to this work our approach allows the verification of SUVs written in C code or other DSLs of mbeddr.

Similarly, the work in [9, 10] introduces a DSL for describing harnesses for testing. This DSL abstracts away from often encountered idioms in order to increase the readability of state-space descriptions. The DSL descriptions allow users to embed code fragments exercising the system under test in its host language. Subsequently test scripts are generated in the target language (Python or Java). Compared to this work, our focus is clearly on the leverage of Promela/Spin capabilities for C code verification; we also offer full IDE support for editing, verifying, and interpreting verification results.

There has been already done work for integrating Promela into common IDEs. For example, the papers [3] and [6] present Eclipse-based IDEs for Promela. Their integrations support Promela users with modern editing facilities like code completion, syntax highlighting, and on-the-fly type checks. Furthermore, language engineering technologies such as Xtext are deployed. While the Eclipse IDE integrations offer modern tool support for building Promela models, none of these contributions support the capability of integrating C code in Promela. Furthermore, the editors are essentially tied to Promela and do not allow users to use higher-level abstractions for capturing common idioms.

Another body of work deals with Promela extensions. The paper [17] presents several light-weighted patterns for using Promela. These patterns are candidates to be lifted at a higher-level DSL. The work in [7] presents an extension of Promela with stronger type checks. While the paper [13] applies language engineering technologies to implement new language features that can be seamlessly added to Promela.

Our tool mbeddr-spin uses the same kind of approach to leverage model-driven code checking with Spin.

8. CONCLUSIONS

The paper presents an approach to improve the usability of environment-driven C code verification using Spin. It proposes a verification harness definition language that is built on top of Promela. For the design of this language, language engineering technologies of the language workbench MPS are used. The new language is introduced by describing its most important concepts. The language captures common usage patterns for defining verification harnesses. The applicability of the language is shown by discussing several categories of SUVs that are often encountered in practice. Compared with the original approach from [12], the new language approach simplifies the harness definition considerably.

Our own future work goes along the following directions. Firstly, we aim to pilot the approach in industrial projects within Siemens to gain further insights in the harness definition for a wider range of C implementations and try to identify further definition patterns and optimized language encodings in Promela. Secondly, we plan to disseminate this technology and train the developers to perform the verification themselves as a much enhanced unit test. Thirdly, we want to address the verification of SUVs with inaccessible internal state. This work is part of a larger effort to bring formal verification technology closer to practitioners. We think that the ultimate solution is to integrate functional verification into the build process of *continuous integration* of software systems, similarly to the integration of automated testing as it is done today.

9. REFERENCES

[1] P. Baudin, P. Cuoq, J.-C. Filliâtre, C. Marché, B. Monate, Y. Moy, and V. Prevosto. ACSL 1.4 : ANSI/ISO C specification language. Technical report, CEA LIST, 2010.

[2] D. Beyer. Reliable and reproducible competition results with benchexec and witnesses report on SV-COMP 2016. In *International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*, 2016.

[3] Z. Brezocnik, B. Vlaovic, and A. Vreze. SpinRCP: the Eclipse rich client platform integrated development environment for the Spin model checker. In *International Symposium on Model Checking of Software (SPIN)*, 2014.

[4] C. Cadar, D. Dunbar, and D. Engler. KLEE: Unassisted and automatic generation of high-coverage tests for complex systems programs. In *Operating Systems Design and Implementation (OSDI)*, 2008.

[5] E. M. Clarke, D. Kroening, and F. Lerda. A tool for checking ANSI-C programs. In *Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*, 2004.

[6] B. de Vos, L. C. L. Kats, and C. Pronk. EpiSpin: An Eclipse plug-in for Promela/Spin using Spoofax. In *International Workshop on Model Checking Software (SPIN)*, 2011.

[7] A. F. Donaldson and S. J. Gay. ETCH: An enhanced type checking tool for Promela. In *Workshop on Model Checking Software (SPIN)*. Springer, 2005.

[8] A. Groce and R. Joshi. Random testing and model checking: Building a common framework for nondeterministic exploration. In *International Workshop on Dynamic Analysis (WODA)*, 2008.

[9] A. Groce and J. Pinto. A little language for testing. In *NASA Formal Methods (NFM)*, 2015.

[10] J. Holmes, A. Groce, J. Pinto, P. Mittal, P. Azimi, K. Kellar, and J. O'Brien. Tstl: the template scripting testing language. *International Journal on Software Tools for Technology Transfer*, pages 1–22, 2016.

[11] G. Holzmann, R. Joshi, and A. Groce. Model driven code checking. *Automated Software Engineering*, 2008.

[12] G. J. Holzmann and R. Joshi. Model-driven software verification. In *Workshop on Model Checking Software (SPIN)*. Springer, 2004.

[13] Y. Mali and E. V. Wyk. Building extensible specifications and implementations of Promela with AbleP. In *Workshop on Model Checking Software (SPIN)*, 2011.

[14] Z. Molotnikov, M. Völter, and D. Ratiu. Automated Domain-Specific C Verification with mbeddr. In *International Conference on Automatic Software Engineering (ASE)*, 2014.

[15] D. Ratiu, M. Voelter, B. Kolb, and B. Schätz. Using language engineering to lift languages and analyses at the domain level. In *NASA Formal Methods Symposium (NFM)*, 2013.

[16] D. Ratiu, M. Voelter, B. Schaetz, and B. Kolb. Language engineering as enabler for incrementally defined formal analyses. In *Proceedings of the Workshop on Formal Methods in Software Engineering: Rigorous and Agile Approaches (FORMSERA'2012)*, 2012.

[17] T. C. Ruys. Low-fat recipes for spin. In *International Workshop on SPIN Model Checking and Software Verification*. Springer, 2000.

[18] M. Sulzmann and A. Zechner. Model checking dsl-generated C source code. In *International Workshop on Model Checking Software (SPIN)*, 2012.

[19] M. Voelter, D. Ratiu, B. Kolb, and B. Schätz. mbeddr: instantiating a language workbench in the embedded software domain. *Automated Software Engineering*, 2013.