# Automatically Generating Test Cases for Safety-Critical Software via Symbolic Execution

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#### Abstract

Automated test generation based on symbolic execution can be beneficial for systematically testing safety-critical software, to facilitate test engineers to pursue the strict testing requirements mandated by the certification standards, while controlling at the same time the costs of the testing process. At the same time, the development of safety-critical software is often constrained with programming languages or coding conventions that ban linguistic features which are believed to downgrade the safety of the programs, e.g., they do not allow dynamic memory allocation and variable-length arrays, limit the way in which loops are used, forbid recursion, and bound the complexity of control conditions. As a matter of facts, these linguistic features are also the main efficiency-blockers for the test generation approaches based on symbolic execution at the state of the art.

This paper contributes new evidence of the effectiveness of generating test cases with symbolic execution for a significant class of industrial safety critical-systems. We specifically focus on SCADE, a largely adopted model-based development language for safety-critical embedded software, and we report on a case study in which we exploited symbolic execution to automatically generate test cases for a set of safety-critical programs developed in SCADE. To this end, we introduce a novel test generator that we developed in a recent industrial project on testing safety-critical railway software written in SCADE, and we report on our experience of using this test generator for testing a set of SCADE programs that belong to the development of an on-board signaling unit for high-speed rail. The results provide empirically evidence that symbolic execution is indeed a viable approach for generating high-quality test suites for the safety-critical programs considered in our case study.

**Keyword** automated test generation, symbolic execution, safety-critical software

## 1 Introduction

Safety-critical software systems control life-critical and mission-critical tasks in airplanes, trains, cars, nuclear power plants and patient monitoring tools. Since failures in these systems can have catastrophic consequences, they must be highly reliable [1]. For this reason, the certification authorities of the specific sectors usually impose strict standards on both the development and the quality control activities [2, 3], in order to ensure the highest possible confidence in the correct behavior of the developed systems.

In this context, *automated* test case generation can play a crucial role for achieving the testing objectives mandated by the standards, while controlling at the same time the associated costs. While the problem of generating a set of test inputs for an arbitrary software program that cover a given target is undecidable, research aims at producing automatic tools that work well "in practice", i.e., in a sufficient number of common cases. The techniques that are more used by current tools are based either on random testing [4, 5], or on search-based testing [6], or on symbolic execution [7, 8]. Random and searchbased testing sample the input space of the target programs, either in a purely random fashion, or guided by the improvement of a *fitness* function, whose value correlates with the coverage objectives to optimize [4, 9, 10, 11, 12]. On converse, symbolic execution [13, 14, 15, 16, 17, 18, 19, 20] systematically explores the execution paths of the program under test: it computes the execution conditions of the explored paths, and solves these execution conditions with the help of an automatic SMT (satisfiability-modulo-theories) solver as, e.g., Yices [21], STP [22] or Z3 [23]. If a solution is found, this is a test input covering the path.

This paper investigates the viability of symbolic execution for automated test generation for safety-critical software. The choice of using symbolic execution is motivated by the importance of fulfilling the relevant test objectives (e.g., the coverage targets required by the certification standards) while testing safety-critical software. By exploring the program paths systematically, symbolic execution should be in principle able to generate at least a test case for every test objective that can be reached on at least an execution path, a goal that the random and search-based techniques cannot generally guarantee. Nonetheless we are also aware of the major challenges of designing test generators based on symbolic execution, which result from common limitations of this technique:

- (i) Coping with the so called *path explosion problem*: Since the number of execution paths of a program grows exponentially with the amount of decision logic in the program, and is generally unbounded for programs that include recursive calls and loops governed with arbitrary conditions, symbolic execution seldom succeeds to analyze all execution paths in finite time. On the contrary, the systematic exploration approach often engages symbolic execution in a very fine-grained analysis of some specific parts of the program execution space, while leaving many other parts entirely untested.
- (ii) Suitably handling non-numeric inputs, i.e., pointers or references to dy-

namically allocated, possibly recursive data structures: For the analysis to be precise, symbolic execution shall be able to discriminate the executions in which the references within the input objects in the heap could be either assigned to null-values, or be alias of each other, or yet correspond to distinct objects, respectively [24]. This further exacerbates the computational requirements for the analysis. The number of objects and object configurations to be discriminated could even be unbounded for inputs defined as recursive data structures.

(iii) Tolerating the limitations of SMT solvers in computing the solutions of complex path constraints: In symbolic execution, failing to solve the execution conditions of a program path can depend on either the path being indeed infeasible, i.e., not executable with any input, or the path constraints being too hard for the current SMT solver to be decided within the allowed time budget, or yet outside of the theories supported by the SMT solver. In the latter cases, the solver is unable to either provide a solution or prove that a solution does not exist. The inability of solving complex path constraints can result in missed test cases, or waste large portions of test budget in the analysis of execution paths that depend on unsatisfiable conditions that the constraint solver failed to pinpoint.

This paper contributes new evidence in support of the research hypothesis that, although the above issues hindering the practicality of symbolic execution may hold for many general-purpose programs, they have reduced impact for a significant class of industrial safety-critical systems, where symbolic execution can therefore work effectively. In fact, safety-critical software often relies on programming languages or conding standards that ban some linguistic features, based on the (empirically motivated) ground that those features are common causes of subtle failures. For example, one of the tenets of safetycritical software development is avoiding unbounded consumption of time or space resources at runtime, to cope respectively with divergence or crashes. For this reason languages for safety-critical software development like SAFERC [1] and  $SCADE^1$  (used in the avionics and in the railway domains, respectively), or coding standards like MISRA<sup>2</sup> (required in the automotive industry) restrict what the programmers are allowed to do. Relevant restrictions include: forbidding programmers from allocating memory dynamically, instead requiring all the memory to be allocated by local or global variables with predictable size; statically bounding the maximum number of iterations of loops; and avoiding recursion. Some consequences of this regime are that in such applications the total number of execution paths is finite, every execution path has a finite depth, and many programming constructs that yield an explosion in the size of the execution state space are not used.

In particular, this paper reports on a case study drawing on our experience with a recent project aimed to develop an on-board signaling unit for high-speed

<sup>&</sup>lt;sup>1</sup>https://www.ansys.com/it-it/products/embedded-software/ansys-scade-suite

<sup>&</sup>lt;sup>2</sup>https://www.misra.org.uk/Publications/tabid/57/Default.aspx#label-dvg

rail, following the ERTMS<sup>3</sup> standard specification, in which we have been recently involved with an industrial partner. This on-board unit is an embedded safety-critical component that shall handle signals from several track-side devices, e.g., transponders deployed along the railway and control units at the stations, and shall notify the driver or even activate the braking devices of the train under some danger conditions. It is currently being implemented with SCADE, a system modelling language and a model-based development environment for embedded software largely adopted in industry<sup>4</sup> [25, 26, 27, 28, 29, 30, 31] and certified according to the CENELEC norms [32]. As we discuss in more detail in Section 2, SCADE allows to specify models with a formalism based on finite state machines, that forbids constructs like dynamic memory allocation, variable-length arrays, non-statically-in-bound accesses to arrays, pointer arithmetic, recursion and unbounded loops. Thanks to these restrictions, SCADE models can be automatically translated to equivalent C programs that guarantee the certification standards [33, 34] required by ERA, the European Union Agency for Railwav<sup>5</sup>.

In the reported case study, we explored whether and to which extent the programming constraints on which the safety-critical software developed in SCADE depends enable the exploitation of symbolic execution for effective automated testing of such programs. In detail, this paper makes the following contributions:

(i) We introduce an original test generator for SCADE programs based on symbolic execution. We refer to this test generator as TECS (Test Engine for Critical Software). TECS builds on the symbolic executor KLEE [15] to render an efficient symbolic analysis of the C programs that the SCADE environment compiles out of the original SCADE models.

The originality of TECS is tightly related to the goal of our case study, in that TECS makes several distinctive design choices that explicitly exploit the programming constraints guaranteed for programs in SCADE. First, TECS exploits symbolic execution to systematically analyze the state machine model that the SCADE program represents. To this end, TECS steers the symbolic executor KLEE through multiple analysis passes of the C program that corresponds to the transition function of the state machine model. In its algorithm, TECS relies on the knowledge that the SCADE translator produces C programs with finite execution paths, thanks to the avoidance of unbounded loops and recursive calls, which guarantees the termination of each analysis pass. Second, TECS exploits the knowledge that all data structures are statically allocated and not recursive, and the size of all arrays is statically specified, which implies that all input data structures are always made of a finite set of statically identifiable distinct

<sup>&</sup>lt;sup>3</sup>www.era.europa.eu/activities/european-rail-traffic-management-system-ertms

<sup>&</sup>lt;sup>4</sup> Ansys, the company that commercializes SCADE and the supporting SCADE Suite modelbased design environment, reports uses of SCADE at Subaru for automotive applications, and for many other safety-critical, embedded applications, including, avionics and flight control, autonomous vehicles and gas turbines. [www.ansys.com/products/embedded-software/ ansys-scade-suite]

<sup>&</sup>lt;sup>5</sup>www.era.europa.eu

fields. Thus, TECS initializes the input data structures at the beginning of symbolic execution by assigning symbolic values to all fields at any nesting level (including the items in all array-typed fields). In this way, TECS induces a specialized, efficient symbolic execution method that shall not cope with discriminating the possible ways of initializing the input data structures and their internal references during the analysis.

- (ii) We report new empirical data that show that TECS successfully computed test cases that both achieve high model coverage of a set of SCADE programs developed by our industrial partner, and revealed (once enriched with suitable assertion-style test oracles) subtle, previously unknown faults for some considered programs. In this way, our case study provides supporting evidence of both the effectiveness of TECS and the suitability of symbolic execution for generating test cases for the considered class of safety critical programs.
- (iii) Furthermore, we report on our experience with using the tool AFL [9], a test generator that is very popular for security vulnerability testing, as a possible replacement of KLEE in our tool. AFL is based on random and search-based input selection heuristics. The results clearly indicate the weaknesses of the random selection approach, which missed many test objectives, further underscoring the beneficial impacts of a systematic exploration of the program state space as in our approach.
- (iv) Yet, for some considered programs, we were able to compare the test cases that TECS automatically produced with the ones that were already manually designed by the developers. The comparison revealed interesting complementarities, thus confirming the usefulness and the effectiveness of our test generator, and further supporting the exploitability of symbolic execution to generate test cases for SCADE models.

This paper is organized as follows. Section 2 surveys the main characteristics of the SCADE programming language, elaborates on the language restrictions that enable our test generation approach, and introduces a sample SCADE program that we use as working example in the paper. Section 3 details the design of the test generator TECS, focusing in particular on the design choices by which TECS exploits the programming constraints that derive from SCADE. Section 4 reports on the case study in which we used TECS to generate test cases for a set of programs that belong to the on-board train unit developed by our industrial partner. Finally, Section 5 surveys the related work in the field, and Section 6 outlines our conclusions and plans for future work on the topics of this paper.

## 2 Safety-Critical Development with Scade

In this section, we survey the main characteristics of the SCADE programming language, motivate our research hypothesis on the exploitability of symbolic execution to generate test cases for programs in SCADE, and introduce a sample SCADE program that we use as working example in the subsequent sections of the paper.

## 2.1 Scade and Characteristics of the Scade Programs

SCADE is a system modelling language that allows the design, implementation and verification of reliable embedded software systems. Ansys Inc. develops the language and commercializes the SCADE Suite development environment, that allows to design embedded cyber-physical systems based on the SCADE language, simulate their behaviour, and generate qualifiable/certifiable code from the models. SCADE is customarily used to develop high-assurance and safety-critical embedded systems in a wide range of application domains as, e.g., avionics, automotive and railway.

The SCADE modelling language belongs to the family of the synchronous languages, such as LUSTRE [35] and ESTEREL [36]. Synchronous languages assume that all the communications and computations in the systems that their models represent are performed instantaneously. A SCADE model is reactive, and structured as a collection of communicating finite-state machines, procedures and functions. Each state may have a hierarchical structure, similar in spirit to, but with richer semantics than, the Statecharts [37] or UML state machine languages [38]. The computation of a SCADE model is performed as a sequence of discrete steps referred to as *execution cycles*. At each execution cycle the outputs and the next state of the model are calculated from the inputs and the current state. At the end of a cycle the execution of the model performs an instantaneous transition to the next state as it enters the next cycle. A valid SCADE model must enjoy the property of running each execution cycle in bounded space and time, and SCADE rejects models that are not deterministic or not deadlock-free. SCADE has both a textual and an equivalent graphical syntax, and the SCADE Suite development environment allows to edit a model in either format.

Integrated in the SCADE Suite development environment, the automatic code generator KCG translates the SCADE models to semantically equivalent programs in either the Ada or the C programming language. In this paper we consider the translation to C programs. The programs generated by KCG are provably equivalent to the SCADE models of which they are a translation. By virtue of the aforementioned properties of the SCADE models, KCG is able to translate them to C programs that also are deterministic, deadlock-free, and that run in bounded space and time. Moreover, in compliance with the SCADE language, KCG aims to ensure that the generated programs are both *embeddable*, i.e., deployable in embedded, resource-constrained environments, and *compliant* with the most demanding safety levels of certification standards as, e.g., DO-178C [2], IEC 61508 [39], EN 50128 [3], and ISO 26262 [40]. To this end, KCG translates a SCADE model to a program expressed in a suitable subset of the C programming language that does not contain programming constructs that are deemed "intrinsically unsafe" or unfriendly with resource-constrained environments. A more precise characterization of the C language subset that KCG uses

as a target for the translation of SCADE models follows:

- Its semantics is unambiguous and precise (e.g., no undefined behaviors);
- It is ISO C18 compliant;
- It conforms to the MISRA C 2012 coding standard rules;
- It has no dynamic memory allocation, all the memory is statically allocated (i.e., no use of heap memory or of variable-length arrays);
- It has no recursive function calls;
- All loops are statically bounded: their number of iterations is determined by constant values known at code generation time;
- No expression has side effects (e.g., no use of pre and post increment operators);
- The code is decomposed into elementary assignment statements to local variables (e.g., no assignment to formal parameters of functions);
- There is no dynamic address calculation ("pointer arithmetic" expressions), no variable aliasing (including the fact that arrays are always accessed by their declaration names via the array subscript operator), no pathological use of the array subscript operator;
- All the array accesses are bounded within the respective array index ranges: the values of the indices of array accesses are determined by constant values known at code generation time.

The restrictions over the C language adopted by KCG are motivated by the required compliance with the highest safety levels of the certification standards that the generated code must address. These standards discourage, or utterly forbid, the use of dynamic memory, aliasing, unbounded iteration and recursion, to ensure that the program always runs in bounded space and time. Furthermore, KCG does not ever produce recursive data structures while translating SCADE programs in C: indeed, the main purpose of recursive data structures is implementing unbounded containers, but since a well-formed SCADE model always runs in bounded space there is no real need for its C translation to use unbounded containers. We remark that the nature of SCADE models—their being deterministic, deadlock-free, and bounded in space and in time—is precisely what allows such a limited fragment of the C language to adequately express the full semantics of the SCADE language.

In the target environment, the embedded software must interact with the sensors and the actuators of the hardware platform. In order to link the SCADE programs to the hardware developers must implement suitable *glue code*, i.e., peripheral drivers, interfacing the KCG code generated from a SCADE model and the external environment. We remark that the test generation problems that we



Figure 1: A sample SCADE model for a car wing mirror controller

consider in this paper refer to the inputs and the outputs of the KCG-generated programs, i.e., the inputs and outputs of the SCADE models, regardless of the possible glue code that binds these inputs and outputs to sensors and actuators of the final system.

### 2.2 Working example

We will use a simple SCADE model to introduce the main concepts and terminology about SCADE, and to show how a SCADE model is converted into C code: this will help the reader in better understanding how our approach described in Section 3 works.

Figure 1 shows a SCADE model that describes a simple controller for the wing mirrors of a car, for which it is possible to activate the behavior of closing the wing mirrors automatically when the car gets locked. The state machine has two states (the boxes in the left and right part of the figure, respectively) that represent whether the car is either locked or unlocked, respectively. The input signal ctrl governs the possible transitions between these two states. The program starts in the state  $CAR_IS\_LOCKED$  (the state on the left of the figure) and then, if ctrl gets set to UNLOCKED the program changes state to  $CAR\_IS\_UNLOCKED$  (the state on the right of the figure). Conversely, if ctrl gets set to LOCKED the program returns to  $CAR\_IS\_LOCKED$ . The signal ctrl can be thought as the input that the car receives from a remote controller.

The program has three further inputs and three outputs. The three inputs are aggregated in the data structure mirrorData, which is referred in both states of the SCADE models in Figure 1. The data structure mirrorDataconsists of two fields: Field mirrorData.automaticControl (dereferenced with the SCADE operator represented as a rectangle in the top part of state  $CAR_{-}$  $IS\_LOCKED$ ) controls whether or not the automatic-closing behavior is currently active; Field mirrorData.mirrorState (dereferenced in both program states) is an array of two items, each defining the latest state (either OPEN or CLOSED) that the driver has set for either wing-mirror. The three outputs are carState, which records the current state of the car, and the two items of array mirrorCommand, which indicate the commands (either OPEN or CLOSED) sent to the wing-mirrors. The carState is simply assigned as LOCKED or UNLOCKED in the two states of the program, respectively. SCADE represents the assignment with an arrow that connects a value to the receiving variable, e.g.,  $LOCKED \rightarrow carState$  represents the assignment of the output carState in the program state CAR\_IS\_LOCKED.

The main behavior of program is to define the commands sent to the wing mirrors when the control system is in each of the two program states, respectively. If the automatic-closing behavior is active, the wing mirrors shall close automatically upon locking the car. Otherwise, they shall just remain as they are. Upon unlocking the car, the wing mirrors shall always return as they were when the car got locked. The program encodes this behavior as follows. When the car gets locked (state  $CAR\_IS\_LOCKED$ ) the outputs mirrorCommand are assigned with the if-then-else block represented as the white rectangle in the bottom-right part of state  $CAR_{-IS}LOCKED$  in Figure 1. The if-then-else block takes *mirrorData.automaticControl* as condition (entering from the top of the block): If the automatic control is active, the outputs *mirrorCommand* are both assigned as the constant *CLOSED* (entering at the top-left corner of the block). Otherwise, if the automatic control is not active, they are assigned to the values in the array *mirrorData.mirrorState* (entering at the bottom-left corner of the block). When the car gets unlocked (state CAR\_IS\_UNLOCKED) the outputs mirrorCommand are always assigned the values of *mirrorData.mirrorState*.

Compiling the SCADE program of Figure 1 with KCG yields the C program excerpted in Figure 2. The program defines the entry function WingMirror-Control\_CarControl (excerpted at the bottom of the figure) that encodes the behavior of the system. This function will be continuously executed at each execution cycle on the target board. As parameters, the program takes pointers to two data structures inC and outC of type inC\_WingMirrorControl\_CarControl and outC\_WingMirrorControl\_CarControl, respectively: inC wraps the inputs that the state machine receives at the beginning of each execution cycle, and outC wraps the outputs of the state machine, along with a special field (WingMirrorFSM\_state\_nxt) that KCG generates to encode the next state of the state machine after each execution cycle. The top part of the code lists the type definitions for both inC and outC data structures, and their nested types.

The body of the entry function consists of two switch statements executed in sequence. The first switch statement calculates the next state, and stores it in the temporary variable WingMirrorFSM\_state\_act. The second switch statement calculates the outputs, and assigns the fields of outC. For example, when the first switch statement computes the next state SSM\_st\_CAR\_IS\_UNLOCKED\_-WingMirrorFSM, corresponding to the model state CAR\_IS\_UNLOCKED, the second switch statement assigns the outputs outC->mirrorCommand to the values of the inputs inC->wingMirrorData.mirrorState, the output outC->carState to UNLOCKED, and the output outC->WingMirrorFSM\_state\_nxt to SSM\_st\_CAR\_-IS\_UNLOCKED\_WingMirrorFSM.

```
typedef struct {
  Lock ctrl;
  MirrorData mirrorData;
} inC_WingMirrorControl_CarControl;
typedef struct {
  MirrorStateArray mirrorCommand;
  Lock carState;
  SSM_ST_WingMirrorFSM WingMirrorFSM_state_nxt;
} outC_WingMirrorControl_CarControl;
typedef struct {
  kcg_bool automaticControl;
  MirrorStateArray mirrorState;
 MirrorData;
}
typedef MirrorState MirrorStateArray[2];
typedef enum {UNLOCKED, LOCKED} Lock;
typedef enum {OPEN, CLOSED} MirrorState;
void WingMirrorControl_CarControl(
  inC_WingMirrorControl_CarControl *inC
  outC_WingMirrorControl_CarControl *outC);
ł
  SSM_ST_WingMirrorFSM WingMirrorFSM_state_act;
  kcg_size idx;
  switch (outC->WingMirrorFSM_state_nxt) {
    case SSM_st_CAR_IS_UNLOCKED_WingMirrorFSM:
      if (inC->ctrl == LOCKED) {
        WingMirrorFSM_state_act =
        SSM_st_CAR_IS_LOCKED_WingMirrorFSM;
      }
      else {
    WingMirrorFSM_state_act =
        SSM_st_CAR_IS_UNLOCKED_WingMirrorFSM;
      break;
    case ...
  }
  switch (WingMirrorFSM_state_act) {
    case SSM_st_CAR_IS_UNLOCKED_WingMirrorFSM:
      kcg_copy_WingMirrorArray(outC->mirrorCommand,
      inC->mirrorData.mirrorState);
      outC->carState = UNLOCKED;
outC->WingMirrorFSM_state_nxt =
      {\rm SSM\_st\_CAR\_IS\_UNLOCKED\_WingMirrorFSM}\ ;
      break;
    case ...
  }
}
```

Figure 2: Excerpt of the C program that KCG generates for the SCADE model in Figure 1



Figure 3: Workflow of TECS

## **3** Generating Scade Test Cases

In this section, we introduce a test generator to automatically generate unitlevel test cases for embedded programs written in SCADE. Our test generator for SCADE programs is built on top of the symbolic executor KLEE, and explicitly relies on the C language restrictions that KCG enforces (as we discussed in Section 2). We designed the test generator with the aim of exploring whether and to which extent these restrictions identify a class of programs that by design mitigate many common sources of open issues for test generators based on symbolic execution. In this section we describe the design of the test generator, while in the next section we report on the effectiveness of the test generator to derive test cases for a set of SCADE programs implemented in a recent project in which we are participating along with an industrial partner.

Figure 3 shows the main components of our test generator, and the workflow that these components comprise. We refer to our test generator as TECS, the *Test Engine for Critical Software*. TECS relies on the KCG compiler, which is part of the cross-compilation tool chain of the SCADE Suite, to convert the SCADE program under test into an equivalent program written in C.

Then, TECS includes a *Driver synthesizer* that augments the obtained C program with an analysis driver written itself in C. The analysis driver embodies the actual analysis algorithm that TECS uses to explore the state space of the program under test: It assigns the program inputs with symbolic values, and then calls the original program multiple times, aiming to trigger the possible transitions of the state machine model that the SCADE program represents. Thus, by executing the analysis driver with symbolic execution, TECS steers multiple analysis passes of the execution paths in the program, with each new pass depending on the (symbolically represented) results of the previous pass. As we explain in detail in Section 3.1, the Driver synthesizer tailors the general analysis algorithm to the specific signature of the program under test.

To accomplish symbolic execution according to the analysis algorithm provided with the analysis driver, TECS relies on KLEE, a well known state-of-theart symbolic executor for programs in C [15]. KLEE generates test inputs for each execution path that the analysis driver induces through the program as follows. First, KLEE performs symbolic execution along each execution path to compute the associated *path condition*, being the path condition a (quantifier free) logic formula that represents the conditions that the inputs shall satisfy for the program to execute along the given path. Then, KLEE attempts to solve each path condition with the STP [41] constraint solver. If a path condition has a solution, this is a set of concrete inputs for executing the corresponding execution path; Otherwise, if there is no solution, the path is *infeasible*, i.e., no input can drive the execution of the program through it. Yet, a further and unfortunate phenomenon is that some path conditions could be formulas that the STP constraint solver cannot solve within the allowed timeout (1 millisecond in our current experiments), and thus the test generation process might result in either or both missed test cases and wasted analysis time. As we already commented in the introduction section, this phenomenon is a common source of ineffectiveness for test generators based on symbolic execution, but also a phenomenon that we hypothesize to be rare for the safety-critical programs in SCADE. Indeed, in the case study that we report in Section 4 we did not experience any unsolved path condition.

Next, TECS filters the execution paths explored during symbolic execution by computing the minimal set of execution paths that guarantee the maximum coverage of the relevant test objectives (Figure 3, *Minimizer*). In fact, maintaining test suites that include a test case for each execution path is by far beyond the typical certification requirements, and cannot be generally afforded by producers. The Minimizer aims to produce a test suite of manageable size, while avoiding to miss test objectives.

As a limitation of our current prototype, TECS delegates the task of the Minimizer to an internal algorithm of KLEE, which can be optionally activated to limit the provided test inputs only to the execution paths that improve statement coverage. This is a sub-optimal minimization behavior, and indeed in the experiments that we report later in this paper we observed that some test objectives that are considered in the SCADE Test tool (which refers to modified condition/decision coverage, a finer criterion than statement coverage) were missed. We discuss the results of the experiments in detail in Section 4. In future releases, we aim to improve our tool by providing a dedicated Minimizer, which is the reason why we illustrated the Minimizer as a logical component of the approach in Figure 3.

As final step, TECS constructs a SCADE test case (Figure 3, *Test synthesizer*) for each of the selected C tests. It thus obtains a test suite in SCADE format, which can be executed within the SCADE test environment.

Below we discuss in detail the design of the Driver synthesizer and the Test synthesizer. We then close this section by remarking the core original ideas that our test generator TECS settles in the analysis algorithm that it instructs with the Driver synthesizer. The Test synthesizer is rather an engineering effort, though important to finalize the generated test suites.

### 3.1 The Driver Synthesizer

The goal of the Driver synthesizer is to augment the C translation of the SCADE model under test with an *analysis driver*, designed to steer the symbolic analysis of the execution paths in the program. In pure technical terms, the analysis driver provides the entry-function that KLEE shall symbolically execute in order to generate test inputs for the program under test. The analysis driver assigns symbolic values to the program inputs, and then calls the target program one or multiple times with the symbolic inputs, to unfold the possible sequences of transitions of the state machine that the program represents. Indeed each call to the target program corresponds to firing a transition of the state machine, and thus each execution path through the analysis driver corresponds to a sequence of state transitions that TECS has to analyze symbolically.

The Driver synthesizer builds an analysis driver that steers KLEE to symbolically execute (and thus generate test inputs for) the program paths and the execution sequences that satisfy the single-state-path-coverage (SSPC) testing criterion with respect to the state machine model implemented in the SCADE program. The SSPC criterion requires to exercise all paths and execution sequences that traverse states at most once [42].

The resulting analysis driver comes in the shape of a general algorithm, representing the overall steering strategy for satisfying the SSPC criterion, and a set of automatically generated hook functions called from the general algorithm, representing the program-specific tailoring of the analysis driver. Algorithm 1 formalizes the general steering algorithm of the analysis driver in pseudo-code, with the calls of the hook functions represented within framed pseudo-code. The hook functions are either functions that already belong to the C program generated with KCG, or functions that the Driver synthesizer generates and injects in the program. The general algorithm indicates that the analysis driver starts in a state that corresponds to the initial state of the program (line 6), with the program outputs initialized to default values by calling the initialization routine that SCADE specifically generates as part of the code of each component (line 5), and considering an initially empty set of visited states (line 7). The hook function default\_values (line 5) for initializing the program outputs with default values is part of the C program generated by KCG. Then, the driver iterates through the loop at lines 8–14, where it calls the program under test once per iteration (line 10), until the execution of the program leads to an already visited state (line 8). Exiting the loop corresponds to an execution sequence that we must consider according the SSPC testing criterion and for which KLEE will then generate a corresponding test input.

At each iteration of the the loop at lines 8–14, the analysis driver triggers the possible state transitions of the SCADE program by first assigning the program inputs with fresh symbolic values (line 9), and then symbolically executing the program under test to analyze the possible execution paths (line 10). For each analyzed path, it saves the current symbolic values of the outputs to enable the TECS Test synthesizer to generate regression oracles later on (line 11), updates the set of visited states (line 12), and iterates with the analysis of the next state

Algorithm 1 The algorithm of the analysis driver

### Let: 1: program be the program under test, 2: *inputs* be a reference to the inputs of the program, 3: *outputs* be a reference to the outputs of the program, 4: $s_0$ be the initial state of the program, 5: $outputs \leftarrow | default values()$ 6: $state \leftarrow s_0$ 7: $visited \leftarrow \emptyset$ while $state \notin visited$ do 8: $inputs \leftarrow | fresh\_symbols()$ 9: $state', outputs \leftarrow | program(state, inputs, outputs) |$ 10: save\_symbolic\_expressions(outputs) 11: $\overline{visited \leftarrow visited \cup \{state\}}$ 12: $state \leftarrow state'$ 13:14: end while

(line 13). The hook functions at the first three steps inside the loop crucially depend on the restrictions that KCG enforces to foster dependable safety-critical software. Below, we explain these hook functions in detail.

Function fresh\_symbols (Algorithm 1, line 9) This hook function assigns the program inputs with symbolic values. The Driver synthesizer generates the code of the hook function  $fresh_symbols$  based on the knowledge that KCG does not generate recursive data structures, dynamic memory allocation or variablelength arrays. This guarantees the viability of unfolding all fields of primitive types that belong to the input data structures at any nesting level, since these fields are necessarily a finite set. Thus, the analysis driver synthesizer customizes the code of function  $fresh_symbols$  such that it assigns each primitive-typed input (received either as an input variable or as a field nested in an input data structure) to a fresh symbolic value, while it initializes all pointer-typed inputs and arrays with references to concrete memory locations.<sup>6</sup> The Driver synthesizer uses the tool ANTLR4 [43] to parse the type definitions in the C program for the sake of generating the code of function  $fresh_symbols$ .

 $<sup>^{6}</sup>$  We remark that, by initializing all pointers and arrays with references to concrete memory locations, our approach guarantees by-design that no memory access through a pointer can ever result into a *symbolic memory access* (a memory access in which the memory location itself – or the base of the array – is a symbolic, non-deterministic value) during symbolic execution. Accessing arrays with symbolic indices can still lead to non-deterministic memory accesses, which KLEE models with formulas expressed in the theory of arrays [41], consistently with the semantics of the program under test. In this case, our approach guarantees that these formulas predicate on concrete, non-overlapping arrays of fixed size, which can be addressed without particular challenges with SMT solvers at the state of the art [41].

```
1 inC_WingMirrorControl_CarControl* fresh_symbols() {
2 inC_WingMirrorControl_CarControl* ret = malloc(sizeof(...));
3 klee_init(&ret->ctrl, "...");
4 ret->wingMirrorData = malloc(2 * sizeof(...));
5 klee_init(&ret->wingMirrorData[0], "...");
6 klee_init(&ret->wingMirrorData[1], "...");
7 return ret;
8 }
```

Figure 4: The hook function *fresh\_symbols* for the sample program of Figure 2

Let us consider, for instance, the working program that we introduced in Figure 1. With reference to the corresponding C program of Figure 2, the Driver synthesizer generates the hook function  $fresh_symbols$  as indicated in Figure 4. By inspecting the considered C program, the analysis driver synthesizer identifies that the data structure of type inC\_WingMirrorControl\_CarControl, which represents the program inputs, includes a field ctrl and a field wingMirrorData, respectively. The former field is defined as an enumeration type, i.e., a primitive type, and the latter field is an array, i.e., a non-primitive type. Thus, the Driver synthesizer inspects the definition of the array, revealing that it consists of two items of primitive type (again an enumeration). The generated function *fresh\_symbols* ultimately consists of C code that initializes a new instance of the data structure in memory (Figure 4, line 2), relies on KLEE (operation *klee\_init*) to initialize the primitive field ctrl with a new fresh symbol (line 3), initializes the non-primitive field wingMirrorData as a new array instance with two items (line 4), and initializes the two items in the array with further fresh symbols (lines 5 and 6).

The operation *klee\_init* for initializing the inputs with fresh symbols takes two main parameters: one is the input to be initialized passed by reference, and the other one is a name (a string of characters) to be associated with that symbolic value. For instance, we might define the name "ctrl" for the fresh symbol that function *fresh\_symbols* associates with the input **ret->ctrl** at line 2. Upon generating test inputs as possible concrete values of the symbols, KLEE will use the provided name to indicate the input data to which those values refer. We postpone to Section 3.2 the discussion on how we specifically define the names for the fresh symbols to facilitate the task of synthesizing SCADE test cases out of the test inputs obtained with KLEE.

**Executing the program under test (Algorithm 1, line 10)** The hook function *program* at line 10 represents a call to the program under test, which is already part of the C code generated with KCG. The program receives the current state, the freshly initialized symbolic inputs and the current values of the outputs, and executes a state transition, possibly yielding a new state and new outputs. When executing *program*, TECS relies on the knowledge that the C translation of a SCADE model consists (by construction) of all deterministic and terminating program paths, and thus the symbolic execution is guaranteed to terminate without need of enforcing any scope bound for the analysis.

Function save\_symbolic\_expressions (Algorithm 1, line 11) This hook function saves the symbolic expressions associated with the outputs after each execution of the program under test. This enables TECS to solve (at a later step) these expressions to concrete values that consistently match with the selected inputs, and use those value to define regression oracles within the test cases. At the state of the art, generating regression oracles is a common functionality offered by most test generators [12]: a regression oracle defines the expectation that the outputs shall be equal to the values observed during the test generation process, which is trivially true when executing the test cases against the program that is being considered, but may provide meaningful insights on possible regressions against future new versions of the program.

The same considerations that we discussed for function *fresh\_symbols*, related to the possibility of unfolding the primitive fields in the input data structures at any nesting level in finite steps, hold as well for function *save\_symbolic\_expressions* with the only change that, in this case, the function unfolds the symbolic expressions associated with all primitive fields that belong to the output data structures of the program. For our working program, TECS customizes function *save\_symbolic\_expressions* to save the symbolic expressions associated with the primitive-typed output carState and the two primitive outputs that comprise the array mirrorCommand.

Technically, function  $save_symbolic_expressions$  generates a fresh symbol for each primitive-typed output, and informs KLEE of the assumption that the new fresh symbol shall be equal to the value of the symbolic expression that is currently associated with the given output. This can be done with the the KLEE API klee\_assume. For instance, for saving the symbolic expression associated with the output carState,  $save_symbolic_expressions$  generates a new fresh symbol (say s) and then calls klee\_assume(s==carState). This leads KLEE to compute a result for the symbol s that reveals the value of carState at the moment when the assumption was evaluated during symbolic execution, consistently with the values that KLEE computed for all other inputs.

Weak transitions We now discuss a refinement of the steering algorithm (Algorithm 1) aimed to handle a special types of state transitions, called *weak transitions*, which can be defined in SCADE models. When a weak transition is fired, the actions that it defines are activated and the state is updated, but the outputs of the target state become active one execution cycle later. Thus, a weak transition requires two, rather than one, execution cycles to complete. During the second cycle the state machine stays in the destination state of the weak transition, that is therefore visited twice.

Algorithm 2 extends the analysis driver to handle weak transitions. This new algorithm is equal to Algorithm 1, but includes the additional steps highlighted with gray-shadowed background. The algorithm has a new dependency on the predicate weak\_transition(state\_a, state\_b) (line 5) that indicates whether or not the transition from  $state_a$  to  $state_b$  is a weak transition. We can deduce this information automatically out of the metadata that SCADE associates with the

Algorithm 2 The algorithm of the analysis driver extended for weak transitions

Let: 1: *program* be the program under test. 2: *inputs* be a reference to the inputs of the program. 3: *outputs* be a reference to the outputs of the program. 4:  $s_0$  be the initial state of the program, 5: weak\_transition be a predicate that is true for state-pairs that correspond to weak transitions. 6:  $outputs \leftarrow default values$ 7: state  $\leftarrow s_0$ 8: visited  $\leftarrow \emptyset$ 9:  $stutter \gets false$ 10: while state  $\notin$  visited do 11:  $inputs \leftarrow fresh\_symbols()$  $state', outputs \leftarrow program(state, inputs, outputs)$ 12:13:save\_symbolic\_expressions(outputs) 14:if ¬ stutter then 15: $visited \leftarrow visited \cup \{state\}$ end if 16:17: $stutter \leftarrow weak\_transition(state, state')$ 18: $state \leftarrow state$ 19: end while

program under test. After each execution step, if a weak transition is fired, i.e., if the predicate *weak\_transition(state, state')* is true at line 17, then the variable *stutter* memorizes the fact. In this case, at the next iteration, the destination state of the weak transition is not added to the set of the visited states (line 14). This allows the program to complete the weak transition, which requires to visit that state once again, and then progress further on.

### 3.2 The Test Synthesizer

The TECS Test synthesizer uses the test inputs obtained with KLEE to construct test cases in SCADE format. Figure 5.b reports a sample test case in SCADE format that was generated with TECS. It consists of two test steps: The first test step sets (SSM::set test statements) ctrl to UNLOCKED, automaticControl to false and mirrorState to OPEN for both wing mirrors, in order to unlock the car and opening the wing mirrors. Thus, the test case doublechecks (SSM::check) that, after this step, carState is equal to UNLOCKED and the outputs mirrorCommand are both assigned to OPEN. When the test case executes the statement SSM::cycle, SCADE executes the test step and checks the values of the outputs accordingly. The second test step switches ctrl to LOCKED, and automaticControl to true, then expecting that the carState moves to LOCKED while issuing mirrorCommand outputs equal to CLOSED.

To synthesize the test cases in SCADE format, the TECS Test synthesizer renders the test inputs that KLEE yielded for a given execution path in the form of suitable *SSM::set* test statements, and renders the regression oracles that KLEE yielded for that path in the form of suitable *SSM::check* test statements. For the execution paths that KLEE explored by issuing multiple calls of the program under test, the corresponding test cases shall include separate

Name of the fresh symbol (field, ty	Test	enum		
field	type	$\mathbf{seq}$	input	value
inC.ctrl	enum Lock	1	0	UNLOCKED
inC.wingMirrorData.automaticControl	boolean	1	false	-
inC.wingMirrorData.mirrorState[0]	enum MirrorState	1	0	OPEN
inC.wingMirrorData.mirrorState[1]	enum MirrorState	1	0	OPEN
outC.carState	enum Lock	1	0	UNLOCKED
outC.mirrorCommand[0]	enum MirrorState	1	0	OPEN
outC.mirrorCommand[1]	enum MirrorState	1	0	OPEN
inC.ctrl	enum Lock	2	1	LOCKED
inC.wingMirrorData.automaticControl	boolean	2	true	-
inC.wingMirrorData.mirrorState[0]	enum MirrorState	2	0	OPEN
inC.wingMirrorData.mirrorState[1]	enum MirrorState	2	0	OPEN
outC.carState	enum Lock	2	1	LOCKED
outC.mirrorCommand[0]	enum MirrorState	2	1	CLOSED
outC.mirrorCommand[1]	enum MirrorState	2	1	CLOSED

(a) The test inputs that KLEE generated for an execution path (through the analysis driver) for the sample SCADE program of Figure 1  $\,$ 

```
#Test step 1
SSM::set ctrl UNLOCKED
SSM::set\ wingMirrorData.automaticControl
                                          false
SSM::set wingMirrorData.mirrorState {(OPEN,OPEN)}
SSM::check carState UNLOCKED
SSM::check mirrorCommand {(OPEN, OPEN)}
SSM::cycle
#Test step 2
SSM::set ctrl LOCKED
SSM::set wingMirrorData.automaticControl
                                          true
SSM::set wingMirrorData.mirrorState {(OPEN, OPEN)}
SSM::check carState LOCKED
SSM::check mirrorCommand {(CLOSED, CLOSED)}
SSM::cvcle
```

(b) The Scade test case synthesized out of the test inputs from  $\ensuremath{\mathsf{KLEE}}$ 

Figure 5: A test case generated for the sample program of Figure 1

a test step (SSM::cycle) for each program call, and the Test synthesizer shall consistently map the test inputs that correspond to each program call with the inputs of each step within the SCADE test cases.

The Test synthesizer relies on a set of naming conventions that the analysis driver enforces when defining the names for the symbolic values. In detail, the analysis driver makes sure that the name of each fresh symbol specifies (i) the name of the input field initialized with the fresh symbol, (ii) the type of the input field, and (iii) the sequence number of the program call for which the analysis driver instantiated the fresh symbol.

For instance, with reference to the the code of function *fresh\_symbols* generated for our working program (Figure 4), the fresh symbol that the analysis driver associates with the input field **ctrl** at the second call of the program under test (for the execution paths that make at least two calls of the program) is named as "field: inC.ctrl, type: enum Lock, sequence: 2". Thus, when KLEE

yields a test input 1 for that symbol, the test synthesizer understands that the value 1 shall be assigned to the input field ctrl at the second program call made in the test case. Moreover, knowing that the field is of type *enum Lock*, it can deduce that the value 1 refers to the second item defined in that enumeration, i.e., the value LOCKED. Thus, the test synthesizer generates the assignment ctrl = LOCKED at second test step.

Figure 5 shows the test inputs (Figure 5.a) that KLEE generates for an execution path through the analysis driver for the sample SCADE program of Figure 1, and the SCADE test case that TECS synthesizes correspondingly (Figure 5.b). The figure indicates the test inputs in tabular form to improve readability. Each row of the table corresponds to a test input from KLEE. The first three columns represent the name that the analysis driver associated with the fresh symbol. As we described above, each symbol name is comprised of a field-, type- and sequence-specifier. The fourth column indicates the specific test input value that KLEE yielded. The fifth column shows the matching enumeration value for test inputs of enumeration types. The test inputs that correspond to the fields of the data structure inC were generated in the hook function  $fresh\_symbols$  of the analysis driver: They indicate the input values for the test case. The ones that correspond to the fields of the data structure outC were generated in the hook function  $save\_symbolic\_expressions$ : They indicate values for regression oracles.

As the table indicates, KLEE generated 14 inputs for the considered execution path. These 14 inputs refer to two subsequent calls of the program under test that occur within the execution path, as the value of the sequence-specifier, either 1 or 2, indicates that the first 7 test inputs map to the first program call, and the following 7 test inputs map to the second program call, respectively.

Thus, TECS synthesizes a SCADE test case consisting of two test steps (Figure 5.b). The first test step sets (SSM::set) ctrl to UNLOCKED, automaticControl to false and mirrorState to OPEN for both wing mirrors. This results in unlocking the car and opening the wing mirrors, and in fact the test case defines the regression oracles (SSM::check) stating that this test step shall lead to a state in which the carState is equal to UNLOCKED and the outputs mirrorCommand are both set to OPEN. When the test case executes the statement SSM::cycle, SCADE executes the test step and checks the values of the outputs accordingly. The second test step switches ctrl to LOCKED, and automaticControl to true, then expecting in the assertions that the carState moves to LOCKED while issuing CLOSED for both mirrorCommand outputs.

### 3.3 Remarks

The method that TECS realizes to initialize the program inputs with symbolic values, execute the program, and save the values of the outputs, would hardly work if we were addressing the symbolic execution of an arbitrary C program. Thus, our design of the test generator TECS is tightly connected to the research hypotheses that this paper formulates about the class of programs identified by programming languages for safety-critical software, out of which we refer to

SCADE as a representative case.

In detail, with reference to the hook functions *fresh\_symbols* and *save\_symbolic\_expressions* that we introduced and discussed in this section, if the inputs and the outputs of the program could be defined of the type of dynamically allocated recursive data structures, the analysis driver that TECS synthesizes might lead KLEE though infinite recursive steps in the attempt to initialize the fields at any nesting level, since the possible nesting levels would be unbounded for a recursive data structure. If dynamic memory allocation had to be considered, symbolic execution should handle pointer-aliases for the pointers present in input data, by considering all the possible alternative initializations in which they could either hold null values, or refer to any compatible memory location that belongs to the input state [24]. If input arrays with non-statically-known length were allowed, there would be no immediate way to initialize them by unfolding their internal items.

With reference to the hook function *program* (which executes the state transitions of the SCADE program under test), TECs relies on the knowledge that the program under test is fully deterministic and does not include unbounded loops or recursion. This assumption guarantees that the analysis driver always analyzes a finite number of execution paths in each pass of the program, and always terminates for each execution path, without need of specifying any customized bound neither in the target program, nor within the symbolic executor. In general, this is impossible for symbolic-execution-based test generators that address arbitrary programs.

## 4 Case Study

In this section we report on a case study where we evaluated the effectiveness of symbolic execution, as instantiated in our tools TECS described in Section 3, for generating test cases for safety-critical software developed in SCADE. We considered a set of SCADE programs developed as part of a project for an on-board signaling unit for high speed rail. This project is currently being developed by an industrial partner, with whom we are collaborating. We used TECS to automatically generate test cases for the considered SCADE programs, and we evaluated our approach in terms of both the ability of TECS to successfully accomplish the test generation process, and the quality of the resulting test suites.

Below we explain the research questions that drove our evaluation, describe the considered SCADE programs, present the experimental setting of the case study, report on the results, and discuss the main threats to the validity of our current conclusions.

### 4.1 Research Questions

In the case study we aimed to answer the following research questions:

- RQ1: Does TECS accomplish test generation within acceptable test budgets?
- RQ2: What is the quality of the test suites that TECS generates?

We answer RQ1 by quantifying how many execution paths TECS actually analyzes when generating test cases for a set of SCADE programs implemented by our industrial partner (presented below in Section 4.2), and how long it takes overall to complete the test generation process for those programs. RQ1 aims to produce empirical evidence that we can effectively exploit symbolic execution to generate test cases for safety-critical software in SCADE. As we explained in Section 3, TECS concretizes this hypothesis by tailoring its implementation of symbolic execution on the restrictions by which KCG fosters by-design safety guarantees in the programs. Thus, as RQ1 states, we aim to empirically confirm whether or not TECS, by its distinctive design, indeed succeeds to accomplish the test generation process within acceptable test budgets.

We answer RQ2 by evaluating the quality of the test suites that TECS generates for the considered programs. We evaluate the quality of the test suites (i) in absolute terms, i.e., by measuring the size and the structural thoroughness of the test suites and by experiencing with the generated test suites to support component-level testing of the considered programs, (ii) in comparison with the manually derived test suites that were already available for three of the considered programs, (iii) in comparison with test suites automatically derived with a search-based test generation approach [9]. RQ2 aims to confirm the merit of generating test cases based on symbolic execution.

### 4.2 Subject Programs

We considered the 37 SCADE programs listed in Table 1. The table defines an identifier (first column) that we use to refer to each subject program in the sequel of the paper, and provides a short description (second column) of the task that each program executes. These programs are part of the on-board signaling unit for high speed rail that our industrial partner is currently developing. For example, the first program, **shunting** implements the Shunting procedure. In the railway terminology, shunting is the process of sorting railway vehicles into complete trains. When a train is in *shunting mode*, the on-board unit is responsible for the supervision of the speed limit that is allowed during the shunting operations, and to stop the train when it passes the defined border of the shunting area. The shunting procedure that we consider as subject program shall handle the messages that the train receives from both the driver and the ground signaling equipment, to make decisions on when activating or deactivating the shunting mode. The other programs implement several control tasks, as checking and verify the consistency of the data that the on-board unit receives from the ground components, computations of information for monitoring and controlling the train, rendering appropriate messages to the driver, and sending commands to the actuators.

Table 1: Subject programs

Subject	#Description
shunting	Sorts railway vehicles into a complete train
dc_1, dc_2,, dc_14	Check data consistency of received messages
radiohole	Deactivates radio connection supervision when train is in a radio hole area
crossnonlx	Monitors a level crossing area that is not protected by external authorities
baliseinfo	Renders messages from on-railway transporders to the driver
emergency_1	Updates on-board data when receiving an emergency message
emergency_2	Acknowledges radio control center when receiving an emergency message
mema	Rejects movement authorities if there are emergency messages
trackside	Receives and stores values from trackside equipments
vbc	Updates the list of known transponders
coordfromrbc	Updates the coordinate system as specified by the ground control
adfactordmi_1	Warns the driver if the railway adhesion factor is slippery
adfactordmi_2	Renders the railway adhesion factor in the GUI
driveridins	Updates the driver ID as indicated through the GUI
eirene	Stores the EIRENE number as indicated through the GUI
ertmslevel	Updates the operating level as indicated through the GUI
natvalues	Verifies the national values of the currently traversed region
networkidins	Updates the identifier of the radio network
rbcidins	Stores the ID of the radio control center ID as indicated through the GUI
trainDataUpdate	Updates the train data stored on board
trainDataInsertion	Inserts new train data among the ones stored on board
message129	Notifies changes of train data to the radio control center
runnumber_1	Updates the train ID on board
runnumber_2	Notifies changes of the train ID to the radio control center

Table 2 summarizes the main statistics on the internal structure of the subject programs, i.e., the number of the states (column #States) and state transitions (columns #Transitions) of the state machine that corresponds to each SCADE program, the number of inputs (column #Inputs) and outputs (column #Outputs) of each SCADE program, and the number of lines of C code that correspond to each program after exporting it with KCG. For the state transitions, the table reports separately the number of weak and strong (non-weak) transitions, since the weak transitions count double in the sequences of transitions that TECS analyzes, as we explained in Section 3.1 (Algorithm 2). The lines of C code refer to the code within the C functions that specifically correspond to each SCADE programs. In fact, each program includes more than 8,000 further lines of code that define the data-types used in the C functions, and which TECS parses with ANTLR4 to instantiate the hook functions of the analysis driver.

For instance, the SCADE implementation of shunting is a state machine with 5 states, 2 weak transitions and 8 strong transitions, in which the states and the transitions are based on computations and conditions that involve 12 input and 14 output variables, respectively, including the variables that represent the messages received and sent from on-board unit. Many subjects (all but shunting, radiohole and crossnonlx) implement computations that the on-board unit shall keep on repeating at each execution cycle, and thus they consist of a single state transition which represents the execution of the computation, and which keeps the program always in the same state. For instance, the dc\_1..14 programs implement data consistency checks that the on-board

Subject	#States	#Transitions		#Inputs #Outputs		$LOC^{(*)}$
Bubjeet	#States	weak	strong	#inputs	#Outputs	100
shunting	5	2	8	12	14	646
dc_1	1	1	-	13	7	175
dc_2	1	1	-	1	2	43
dc_3	1	1	-	5	3	95
dc_4	1	1	-	3	4	62
dc_5	1	-	1	3	1	32
dc_6	1	1	-	3	4	67
dc_7	1	-	1	3	1	32
dc_8	1	-	1	2	1	30
dc_9	1	1	-	5	15	464
dc_10	1	1	-	3	9	239
dc_11	1	1	-	1	3	69
dc_12	1	1	-	14	17	96
dc_13	1	1	-	3	7	67
dc_14	1	-	1	1	1	35
radiohole	3	2	1	2	2	361
crossnonlx	3	2	1	6	4	556
baliseinfo	1	1	0	1	2	147
emergency_1	1	1	0	9	4	865
emergency_2	1	1	0	9	6	711
mema	1	1	0	4	1	798
trackside	1	1	0	3	0	225
vbc	1	1	0	7	1	1,011
coordfromrbc	1	1	0	1	1	366
adfactordmi_1	1	1	0	3	1	125
adfactordmi_2	1	0	1	1	1	54
driveridins	1	1	0	1	1	262
eirene	1	0	1	3	1	124
ertmslevel	1	0	1	1	1	109
natvalues	1	0	1	1	1	265
networkidins	1	0	1	1	1	109
rbcidins	1	1	0	1	1	189
trainDataUpdate	1	1	0	2	19	136
trainDataInsertion	1	0	1	2	1	291
message129	1	1	0	5	1	353
runnumber_1	1	1	0	1	1	154
runnumber_2	1	1	0	4	1	116

Table 2: Statistics of the subject programs

<sup>(\*)</sup> C code LOC values refer to the lines of code in the C functions specific of each SCADE program, but each program includes more than 8,000 additional lines of code of data-type declarations, which define the data structures that comprise the inputs and the outputs of the programs.

unit shall perform at each execution cycle. These programs define either a weak or a strong transition according to whether or not, respectively, the check that they implement depends on feedback loops with their own outputs.

At the level of the C code, the considered programs range between 30 and 1,011 lines of code (plus the code defining the data types, i.e., as said, more than 8,000 additional lines of code) being program dc\_8 and program vbc the smallest and the largest program, respectively.

#### 4.3Experimental setting

Our case study consisted of a set of experiments, one for each of the subject programs listed in Table 2, in which we ran TECS to generate test cases for the subject programs, executed the test cases in the SCADE Suite and collected model coverage data.

We ran TECS on cloud facility hosted at our university, using a virtual machine equipped with Linux Ubuntu, 48 cpus, 150 GB of ram memory, which allowed for running multiple instances of TECS in parallel.

We handled the SCADE programs with SCADE Suite Version 2020 R2, which includes the corresponding version of the KCG compiler that we use to obtain the C version of the subjects programs. We executed the test cases with the tool SCADE Test Version 2020 R2.

During the experiments, for each subject program, we tracked the number of paths that TECS identified during the symbolic execution phase, measured the time that it took to complete the test generation process, counted the number of test cases that it generated, and computed the model coverage that the test cases achieve against the SCADE programs.

For measuring the model coverage of the test cases we relied on the SCADE Test tool, which automatically computes the model coverage while executing the test cases. The coverage computed with SCADE Test refers cumulatively to the portion of executed states, and the modified condition/decision coverage of the transition guards.

In the case of programs shunting, radiohole and crossnonlx we were able to compare the test cases generated with TECS with manually selected test suites that were already available for those programs at the time of our experiment. We compared the manual and the automatic test suites with respect to their difference in model coverage, focusing on the items that either test suite covers and the other one does not.

For all other subject programs, the engineers at our industrial partners decided to rely directly on our tool (as TECS in fact became available while those programs were being implemented), aiming to optimize their effort for designing and implementing the test cases for those programs. To this end, they augmented the test cases generated with TECS with (manually defined) assertionstyle test oracles, aiming to obtain test suites that could be readily used for component-level testing of the considered programs (other than for future regression testing of those programs). This resulted in a semi-automatic approach to component-level testing empowered by our tool TECS, and allowed us to further validate the quality of the test suites generated with TECS in terms of usefulness for detecting component-level failures in the context of our industrial project.

We remark that, on one hand, this choice of our partner affected our ability to extensively crosscheck the differences in effectiveness of automatically and manually generated test suites, respectively, since no manual test suite existed to compare with for any subject program but shunting, radiohole and crossnonlx; On the other hand we believe that the choice of dismissing fully manual testing in favour of working with semi-automatic test cases (obtained by enriching with assertions the ones generated with TECS) supports the positive perception of our industrial partner on the effectiveness of our approach.

			#test steps			
$\mathbf{subject}$	time (s)	#paths	#tests	avg	max	coverage
shunting	286	3,367	20	3	5	86%
dc_1	2	616	8	2	2	91%
dc_2	<1	2	2	2	2	100%
dc_3	<1	16	6	2	2	100%
dc_4	<1	3	2	2	2	92%
dc_5	<1	4	2	1	2	89%
dc_6	<1	3	2	2	2	90%
dc_7	<1	4	2	1	2	80%
dc_8	<1	4	3	1	2	83%
dc_9	2	208	9	2	2	100%
dc_10	<1	64	9	2	2	93%
dc_11	<1	3	2	2	2	100%
dc_12	<1	3	3	2	2	72%
dc_13	<1	20	4	2	2	98%
dc_14	<1	4	2	1	1	82%
radiohole	117	45	6	3	3	95%
crossnonlx	647	294	13	3	3	84%
baliseinfo	1	3	3	1	2	97%
emergency_1	15	28	14	1	2	94%
emergency_2	29	8	6	1	2	82%
mema	23	17	7	1	2	89%
trackside	1137	3	3	1	2	99%
vbc	164	77	12	1	2	94%
coordfromrbc	41	7	5	1	2	83%
adfactordmi_1	1860	3	3	1	2	85%
adfactordmi_2	1	2	2	1	1	96%
driveridins	5	10	10	1	2	89%
eirene	3	3	3	1	1	94%
ertmslevel	2	3	3	1	1	94%
natvalues	1230	4	4	1	1	90%
networkidins	1	3	3	1	1	94%
rbcidins	3	4	4	1	2	95%
trainDataUpdate	47	2	1	1	2	89%
${\it trainDataInsertion}$	28	4	3	1	1	95%
message129	99	80	10	1	2	83%
runnumber_1	2	3	3	1	2	94%
runnumber_2	3	22	7	1	2	92%

Table 3: Results of TECS for the subject programs considered in our case study

### 4.4 Results

Table 3 summarizes the data on the execution of TECS in our experiments, and the test cases that it generated. For each subject program (column *program*), the table reports the time in seconds taken to complete the overall test generation process (column *time*), the number of execution paths analyzed with symbolic execution (column #paths), the number of test cases generated after executing the minimization step (column #tests), the average and maximum number of test steps within the test cases (columns  $\#test \ steps$ ), and the model coverage of the test cases (column *coverage*).

### Test budget requirements (RQ1)

Overall, the data in Table 3 support a positive answer to the research question RQ1 on whether TECS accomplishes the test generation process within acceptable test budgets. Furthermore, as TECS completed in finite time in all experiments, these data also support our hypothesis that, thanks to the language

subject	time (s)	#paths	#queries	>1  ms
radiohole	117	45	484	0
crossnonlx	647	294	502	0
emergency_2	29	8	280	0
mema	23	17	122	0
trackside	1137	3	1305	0
vbc	164	77	279	0
coordfromrbc	41	7	155	0
adfactordmi_1	1860	3	2530	0
natvalues	1230	4	1296	0
trainDataUpdate	47	2	215	0
trainDataInsertion	28	4	121	0
message129	99	80	133	0

Table 4: Data on the queries issued to the constraint solver

restrictions that SCADE embraces to promote safe programs, we can exploit symbolic execution to efficiently explore the execution space of the programs under test without need of specifying custom bounds for the analysis.

In detail, for most subject programs, TECS took a few seconds to complete the test generation process. It took more than 1 minute only for 8 out of 37 subject programs, and more than 10 minutes only for 4 programs, namely, crossnolx, trackside, adfactordmi\_1 and natvalues, the maximum time being 31 minutes (1,860 seconds) in the experiment with program adfactordmi\_1.

In all experiments TECS used most computation time to complete the symbolic execution with KLEE, under the guidance of the TECS analysis driver, while the other phases of TECS, i.e., synthesizing the analysis driver, and synthesizing the test cases in SCADE format, took negligible time.

We investigated in further detail the experiments in which the time budget was not justified by the (low) number of symbolically executed paths. For these cases, we investigated whether the time budget was bounded by some complex execution conditions that took long time for the constraint solver to compute the solutions. To this end, we logged the number of queries that the symbolic executor issued to the constraint solver, and the queries for which the constraint solver took more than a specified time. Table 4 shows these data in particular for the subject programs (column *subject*) for which TECS executed for a number of seconds (column *time*) higher than the number of symbolically analyzed execution paths (column # paths). The table reports the number of the queries issued in total to the solver (column #queries) and restricted to the ones that took more than a millisecond to be solved (column >1). As the table shows, indeed no query took more than a millisecond, confirming that the execution conditions generated during the analysis of the SCADE programs result in simple constraint solving problems. For these programs we were able to map the execution time to the large data structures that comprise their inputs, which required the initialization and the handling of many symbolic values during symbolic execution.

### Quality of the Test Suites (RQ2)

Table 3 shows that the test suites that TECS generated in our experiments consist of a minimum of 1 test case, for program trainDataUpdate, up to a maximum of 20 test cases for shunting. The number of corresponding test steps is either 1 or 2 in all test cases generated for the programs that consist of only a strong or a weak transition, respectively, while it is higher for the three programs that define SCADE models with more states and transitions, i.e., shunting (5 states, 10 transitions), radihole (3 states, 3 transitions) and crossnonlx (3 states, 3 transitions). For these programs, the generated test cases consist of 3 test steps on the average, up to a maximum of 5, 3 and 3 test steps for shunting, radihole and crossnonlx, respectively.

The generated test suites achieved a model coverage of 100% for 4 subject programs, at least 90% for 19 further programs, at least 80% for 13 programs, and 72% in the only case of program dc\_12.

**Uncovered Items** We inspected the programs with uncovered items in further detail, to investigate the reason why TECS missed the generation of test cases that cover those items. We tracked the uncovered items to four distinct motivations:

- Items that depend on infeasible program paths: In fact, many subject programs include infeasible paths, the most frequent case being the one of programs structured with some (sub-)procedures, where the procedures define general algorithms, but the program calls them only in specialized contexts (e.g, with constant values passed for some parameters) and thus inhibits the possibility of executing some branches (e.g., the branches that depend on parameter values different than the used constants).
- Unreported coverage: The SCADE Test tool does not report the coverage of the items that, although executed during the test cases, do not map to any observable output of the SCADE operators in the programs under test. In the considered programs, this happens for a set of operators defined to update stored data: these operators take an input, and use it to do the update, without producing any explicit output. This leads to the SCADE test tool to misleadingly classify some items of our subject programs as uncovered. As we are discussing with our partner, this observation calls for some refactoring of the mentioned operators, to improve the precision of the coverage measurements.
- Functional behaviors out of the scope the single-state-path-coverage testing criterion that TECS uses for steering the test generation process: We observed uncovered functional behaviors in program shunting. The SCADE model of this program includes two model states in which the train expects a message from the ground equipment. These states implement the *degraded behavior* of assuming that the ground equipment is not responding, if the expected message is not received within a specific number

of execution cycles. As a matter of facts, these behaviors correspond to execution sequences that iterate in the same state for multiple execution cycles, and are thus out of the scope of the single-state-path-coverage testing criterion that TECS is designed to satisfy.

• Uncovered modified condition/decision targets: As we commented in Section 3 while discussing the Miminizer step of TECS, a limitation of the current implementation is to select test cases based on statement coverage, which is a grosser grained criterion than the modified condition/decision coverage of transition guards considered in SCADE Test. This resulted in a few uncovered modified condition/decision targets in the current experiments, even if TECS analyzed all execution paths. As said, we aim to overcome this limitation of TECS in future release.

Out of the above cases, only the last two map to limitations of our approach. While the former of these limitations suggests the strategy of complementing the automatically generated test cases for the programs with missing coverage (by searching for functional behaviors that require iterating multiple times though the same state), the latter could be mitigated by improving the implementation of TECS. We evaluated the room for the coverage improvement that we might achieve with a different strategy for selecting test cases out of the symbolically analyzed execution paths. To this end, we re-executed TECS after disabling the Miminizer option in KLEE, thus making TECS compute exactly one test case for each symbolically analyzed execution path. Table 5 compares the number of test cases and the coverage results that we achieved with and without the Minimizer, respectively (but for program shunting for which the high number of test cases computed without Minimizer - 3,367 test cases - exceeded the capability of SCADE Test to execute the test suite). In the table, we highlighted in bold the 6 cases in which the coverage rate improved without using the Minimizer. The amount of improvement was 1% for radiohole and message129, 2% for crossnolx and emergency\_2, 4% for mema, and up to 7% for dc\_1.

**Comparison with Manually Derived Test Cases** In the case of the subject programs shunting, radiohole and crossnonlx we were able to compare the test cases generated with TECS with manually selected test suites that were already available for those programs at the time of our experiment. These test suites were designed in a functional fashion based on the software requirements specified for the program, using the model-based test criterion of executing at least once all non-cyclic paths of the state machine and all conditions involved in the state transitions. The engineers reported to us that the analysis of the requirements, the selection of the test cases and their manual implementation in a the test suite took overall 16 man-hours (two days of work), 3 man-hours (about half day) and 9 man-hours (about one day) for shunting, radiohole and crossnlnlx respectively. They tracked the main challenges to i) devising a suitable functional partitioning of the relevant cases to be tested (which in turn required to reiterate multiple times the study and the analysis of the require-

	with Minimizer		no Minimizer		
$\mathbf{subject}$	#tests	coverage	#tests	coverage	
shunting	20	86%	3,367	n.a.	
dc_1	8	91%	616	98%	
dc_2	2	100%	2	100%	
dc_3	6	100%	16	100%	
dc_4	2	92%	3	92%	
dc_5	2	89%	4	89%	
dc_6	2	90%	3	90%	
dc_7	2	80%	4	80%	
dc_8	3	83%	4	83%	
dc_9	9	100%	208	100%	
dc_10	9	93%	64	93%	
dc_11	2	100%	3	100%	
dc_12	3	72%	3	72%	
dc_13	4	98%	20	98%	
dc_14	2	82%	4	82%	
radiohole	6	95%	45	96%	
crossnonlx	13	84%	294	86%	
baliseinfo	3	97%	3	97%	
emergency_1	14	94%	28	94%	
emergency_2	6	82%	8	84%	
mema	7	89%	17	93%	
trackside	3	99%	3	99%	
vbc	12	94%	77	94%	
coordfromrbc	5	83%	7	83%	
adfactordmi_1	3	85%	3	85%	
adfactordmi_2	2	96%	2	96%	
driveridins	10	89%	10	89%	
eirene	3	94%	3	94%	
ertmslevel	3	94%	3	94%	
natvalues	4	90%	4	90%	
networkidins	3	94%	3	94%	
rbcidins	4	95%	4	95%	
trainDataUpdate	1	89%	2	89%	
trainDataInsertion	3	95%	4	95%	
message129	10	83%	80	84%	
runnumber_1	3	94%	3	94%	
runnumber_2	7	92%	22	92%	

Table 5: Results of TECS with and without the Minimizer

cov = n.a., if SCADE Test failed due to too many test cases

ment documents), ii) analyzing the implementation to identify suitable input and test step sequences for exercising the identified set of relevant cases, and iii) rendering the test cases in the specific language and format required by the SCADE test tool (that we exemplified in Figure 5.b).

Table 6 reports the main statistics of the manual test suites (columns *Manual test suite*) for the three considered programs, sided to the statistics of the test suites that TECS generated (columns TECS) for each of the programs. For each test suite we report the time taken to generate the test suite (column *time*), the number of test cases (column #tests) and the corresponding model coverage (column *coverage*).

The manually derived test suites are sightly more compact in terms of number of test cases than the automatically generated counterparts, but it is clear that pay higher costs in terms of working effort (several hours) in comparison with the relatively shorter time that developers must wait to obtain the test cases with TECS. In terms of coverage, the manual test suite of **shunting** 

	M	anual tes	t suite	TECS			
$\mathbf{subject}$	time	#tests	coverage	time	#tests	coverage	
shunting	16 h	15	95%	286 s	20	86%	
radiohole	6 h	1	94%	117 s	6	95%	
crossnonly	9 h	3	80%	647 s	13	84%	

Table 6: Comparison between automatically and manually derived test suites

achieves higher model coverage than the test suite that TECS generated for this program, but TECS achieved higher model coverage than the manual test suites for radiohole and crossnolx.

We analyzed the difference in the coverage data, focusing in particular on the items of the coverage domain that either test suite hits and the other one does not. In detail, for **shunting**, the manually designed test suite successfully executed the degraded behaviors (since they correspond to a specific transitions indicated in the requirements) that TECS missed as we already commented above. On the other hand, the manually designed test suite missed some possible combinations of the conditions that participate in the transition guards, some of which were hit with TECS thanks to the systematic analysis of all execution paths in the program. Instead, we did not find any manually tested behavior that TECS did not cover in **radiohole** and **crossnonlx**, where TECS was in fact able to cover some additional rare combinations.

In summary, our case study indicated that the test generation approach that we propose in this paper, as instantiated in the tool TECS, successfully exploits symbolic execution to generate high-quality test suites for safety-critical programs in SCADE, thus confirming the main research hypothesis of this paper. The test suites that we automatically generated with TECS in our experiments readily satisfied most domain-relevant test objectives, unveiling at the same time small portions of test objectives that require dedicated handling. This straightforwardly suggests a combined approach in which the testers of safetycritical software can efficiently start working with the test cases automatically computed with TECS, and then complementarily concentrate on the yet-missed behaviors, thus crucially improving both costs and the effectiveness of their test-design efforts.

Usefulness of Tecs for semi-automatic component-level testing To further investigate the quality of the test suites generated with TECS, we worked jointly with our industrial partner to exploit those test suites for componentlevel testing of the considered programs. To this end, the test suites generated with TECS were augmented with assertion-style test oracles defined by test engineers based on the documented requirements, thus resulting in a semi-automatic approach to generating the component-level test cases. Manually adding the assertions took limited effort, a few minutes per test case: It required the test engineers to crosscheck the concrete inputs already provided in the test cases with the expectations defined in the requirement documents. This, we remark, is a radically simpler task than the manual effort quantified in Table 6, to de-

Table 7: Faults identified in the subject programs considered in our case study subject fault

subject	lault
dc_10	Wrong amount of data written in a queue
	Wrongly defined algorithm
$\operatorname{coordfromrbc}$	Missing update of a state variable
	Array updated with index starting at second (instead of first) item
emergency_1	Output value out of expected range
	Wrongly defined algorithm
emergency_2	Interrelated variables updated in wrong sequence
total	7 faults

sign and implement the test cases from scratch, which encompasses a very much larger set of time consuming activities (such as, identifying a functional partitioning out of the requirements, devising suitable test steps and inputs, and implementing the SCADE test cases from scratch).

Table 7 describes the faults that we identified by executing the test suites obtained in this way. Overall we revealed 7 previously unknown faults in four of the subject programs considered in our experiment. These results support the usefulness of the test suites generated with TECS for component-level testing.

**Comparison with search-based testing** We investigated if our approach could work also by using search-based random testing heuristics in place of symbolic execution. To this end, we implemented an alternative version of TECs that used the test generator AFL [9] instead of KLEE to produce the test inputs. AFL is a test generator that is very popular for security vulnerability testing: it starts by performing random mutations on a set of (seed) inputs provided by developers, and then progresses in search-based fashion by considering the newly generated inputs that increase code coverage as additional seeds. In our setting we executed AFL on the analysis-driver programs generated by TECS, providing initial seeds that included an input value for each program input that TECS handled symbolically when using KLEE: For each subject program, we seeded AFL with the input values from the the first test case that we had generated when using KLEE.

The task of AFL was then to discover (by means of its search-based heuristics) further input values, as needed to cover the branches of the program under test. Technically, we exploited the feature of AFL to feed back its own test generation mechanism with the test cases that execute new branches. Upon identifying test inputs that make the program execute new branches, AFL saves those test cases in a queue, aiming to consider them as possible seeds at next steps. Thus, for each subject program, we proceeded as follows: we executed AFL for 5 hours; We used our tool to translate the test cases in the final queue into test cases in SCADE format; We executed the test cases with SCADE Test to collect the corresponding coverage data. We also repeated each test generation attempt 3 times to control for the random characteristics of AFL.

Table 8 reports on test cases generated with AFL for the programs considered in our case study (but program natvalues for which AFL unexpectedly generated a broken instrumentation that made the program crash deterministi-

	TECS		P P		
$\mathbf{subject}$	#tests	coverage	#tests	coverage	diff.
shunting	20	86%	12	46%	40%
dc_1	8	91%	16	89%	2%
dc_2	2	100%	1	100%	0%
dc_3	6	100%	5	100%	0%
dc_4	2	92%	2	86%	6%
dc_5	2	89%	1	89%	0%
dc_6	2	90%	3	84%	6%
dc_7	2	80%	1	50%	30%
dc_8	3	83%	1	50%	33%
dc_9	9	100%	6	100%	0%
dc_10	9	93%	6	93%	0%
dc_11	2	100%	1	100%	0%
dc_12	3	72%	3	60%	12%
dc_13	4	98%	4	82%	16%
dc_14	2	82%	1	64%	18%
radiohole	6	95%	4	68%	27%
crossnonlx	13	84%	6	19 %	65%
baliseinfo	3	97%	2	45%	52%
emergency 1	14	94%	1	6%	88%
emergency 2	6	82%	6	54%	28%
mema	7	89%	5	41%	49%
trackside	3	99%	5	20%	79%
vbc	12	94%	3	40%	54%
coordfromrbc	5	83%	7	57%	26%
adfactordmi 1	3	85%	2	71%	14%
adfactordmi 2	2	96%	3	96%	0%
driveridins	10	89%	2	65%	24%
eirene	3	94%	3	66%	28%
ertmslevel	3	94%	4	88%	6%
natvalues	4	90%	-	-	-
networkidins	3	94%	2	75%	19%
rbcidins	4	95%	2	49%	46%
trainDataUpdate	1	89%	4	60%	29%
trainDataInsertion	3	95%	6	89%	6%
message129	10	83%	8	77%	6%
runnumber 1	3	94%	2	70%	24%
runnumber 2	7	92%	7	93%	-1%

Table 8: Comparison between TECs and AFL

cally at runtime). The table indicates the information of the test cases generated with TECS when equipped with KLEE (columns TECS), in comparison with the number of test cases and corresponding model coverage data achieved with AFL (columns AFL), and shows the difference between the coverage measurements in either case (column diff).

The data in the table indicate that the two approaches led to generating test suites of comparable size in most cases, but the model coverage achieved with AFL was often significantly lower than the coverage achieved with TECS. AFL achieved the same amount model coverage as TECS for 7 programs (namely, dc\_2, dc\_3, dc\_5, dc\_9, dc\_10, dc\_11 and adfactordmi 2), achieved more coverage than TECS only for 1 program (namely, runnumber 2), and achieved less coverage than TECS for the remaining 28 programs. In the 28 cases in which TECS outperformed AFL, the difference in coverage ranged between 2% and 88%, with a median of 26%. In the only case in which AFL outperformed TECS, the difference in coverage was rather limited (1%) due to a single MC/DC objective that TECS did not cover because it missed a specific truth value for a

condition that did not belong to the path condition of the corresponding execution path, while AFL could hit by mutating inputs at random. We interpret these data as clear evidence that a tool like AFL does not suite for our goal of testing safety-critical software, and we believe that the type of weaknesses that we observed by experiencing with AFL likely generalize to search-based test generators at the state of the art.

### 4.5 Threats to validity

The main internal threats to the validity of our findings are concerned with the risk of implementation errors in TECS (that could bias our results), and with use of coverage indicators to evaluate the quality of the test suites.

We extensively tested TECS to ascertain its correctness, and manually crosschecked several result samples. For the implementation of the symbolic execution phase, which is at the core of the results that we computed with TECS, we relied on KLEE, a state of the art symbolic executor actively maintained and largely used in the community. Thus we are confident in the validity of the results that we obtained with TECS.

We evaluated the quality of the test suites that TECS computed in our experiments based on the model coverage indicators obtained with the tool SCADE Test. We drew on the documentation provided from Ansys and on the advising of the industrial partner with whom we are collaborating, to reckon that the coverage indicators computed with SCADE Test correspond to domain-relevant coverage requirements. However, we are well aware that any coverage measurement is just a proxy of the effectiveness of the test cases, and we cannot take for granted that high coverage rates necessarily correspond to high fault-detection power. We attacked this issue by showing that the test suites generated by our tool, once complemented with assertion-style test oracles, succeeded in revealing component-level faults of the considered SCADE programs. We look forward to experiencing TECS on further SCADE programs that are currently being developed in the project, to collect further data on which faults we can indeed detect with the help of the test cases generated with TECS.

The external threats to validity relate to the extent to which our finding can generalize. So far, we experienced TECS against the set of subject programs considered in this paper, which are admittedly only a small sample of the possible safety-critical programs. Nonetheless, on one hand, these programs are a representative sample of the safety-critical software that our industrial partner typically develops, following the most prominent certification standards in the railway sector; On the other hand, the restrictions that SCADE embraces to promote the safety of the programs are common to other programming languages for developing safety critical software, e.g., SAFERC. Thus, we believe that our result might in fact generalize.

## 5 Related Work

We surveyed the most relevant techniques for automated test generation for software programs in the introduction of this paper, encompassing test generators based on random testing, search-based testing and symbolic execution. Random testing and search-based testing derive test cases by either randomly sampling the possible program inputs or based on dynamic data about the execution of the programs. Symbolic execution systematically unfolds the execution space of the programs under test and generates test cases by solving the execution of the possible program paths. Then we have then described our approach to test case generation for safety-critical programs in SCADE, which is based on symbolic execution, and compared our approach with a analogous embodiment based on search-based testing by referring to the tool AFL. Other results on the effectiveness of automated test generation in safety critical systems are provided in [44, 45].

The research that we described in the paper is also related to other approaches for automated model-based testing, to methods for formally specifying and verifying safety-critical software, and to other pieces of research on verifying programs in SCADE.

### 5.1 Automated model-based testing

Our approach can be seen as related to *model-based testing*, which derives test cases by analyzing program specifications or program behaviors expressed in suitable modelling languages, e.g., UML class diagrams, state machines or sequence diagrams [46, 38]. Model-based testing has been successfully applied to complement verification of formal specifications expressed in languages as B, Z or VDM [47]. For a comprehensive survey of model-based testing we refer the readers to the work of Utting et al. [48] and Dias Neto et al. [49].

The approach that we presented in this paper addresses the test generation problem based on the analysis of the execution paths in the programs, and naturally lends itself to complement or be complemented with further test cases generated either manually or yet automatically in model-based fashion.

In particular our approach shares similarities with the ones of Polyglot [50, 51] and SAUML [52], which exploit symbolic execution to generate test cases for systems modeled with statechars and UML-RT state machines, respectively. Polyglot is similar to TECS in that it translates statecharts to programs (specifically programs in Java) and then exploits symbolic execution (by means of the symbolic executor SPF [53] that addresses Java), to generate test cases that achieve path coverage up to some specified depth. SAUML extends symbolic execution to directly analyze the UML-RT models (i.e., it works without converting the models to programs) to check properties like reachability and invariants, and to generate test cases. Our approach differs from both these approaches in the way TECS distinctively uses symbolic execution within an analysis algorithm tailored on the characteristics of the SCADE models, which foster programs with finite path spaces and input data structures comprised of

finite sets of distinct fields.

### 5.2 Formal methods for safety-critical software

Safety-critical systems need to strictly comply with their requirements as they were elicited in the earliest phases of the development process. Formal methods [54] define one or more languages with mathematically precise semantics that can be used to describe the requirements, the domain constraints and the designs, and to prove or disprove relevant properties thereby, e.g., absence of deadlock or unreachability of unsafe states. Most formal method define mathematically rigorous procedures to ensure that the artifacts produced at every step of a development process *refine* the artifacts produced at earlier steps, thus preserving all their relevant properties. The downside of these approaches is the degree of mathematical sophistication that they demand to software engineers and designers, who should be able to model a system with a formal specification, prove (or disprove) its properties, refine an abstract (not directly computable) specification progressively to a concrete (computable) one, and translate a concrete specification to an executable program in a given programming language. To this end, formal methods are often accompanied with tools that assist in performing their tasks, with various degrees of automation, which anyway hardly balance the aforementioned complexity.

Formal methods differ for the breadth of their scope. At one end of the spectrum, methods like B or its successor Event-B [55] aim at producing a complete, correct-by-construction approach, encompassing all the phases of the development lifecycle. These methods usually refrain from testing the final implementation, in the assumption that having proved both a sufficient set of correctness properties on the abstract designs, and their preservation through the refinement steps may suffice to ensure that the final program is correct by-construction. Other formal approaches do not have the generality of a full correct-by-construction method, and focus only on assisting a well defined part of the software development process. This is the case of Alloy [56], a language and a tool for modeling systems that is suited to assist the specification and abstract design activities. Similarly, Z [57] is customarily used as a system modeling language, although there also exists a well-established theory of refinement for Z [58].

Formal approaches that do not have the generality of correct-by-construction methods can benefit from software testing to provide some degree of assurance that the derived implementations comply with the corresponding requirement specifications. Even correct-by-construction approaches might require testing, to cope with the *weak* (i.e., unproved) points of the refinement and translation chain, or simply to comply with certification requirements [47].

### 5.3 Automated test generation for Scade models

SCADE can be regarded as a formal modeling approach focused on the detailed design and implementation phases of the software lifecycle. The SCADE lan-

guage is derived from the synchronous dataflow programming languages LUS-TRE [35], with some programming constructs derived from the programming language ESTEREL [36] and from the graphical, state-machine-based language SyncCharts [59]. SCADE has formally defined semantics. All its constructs are computable, and therefore it is suited to express concrete designs rather than requirements and high-level system models. The SCADE suite provides a modelbased test coverage measurement tool that, from a SCADE model and a test suite, calculates the coverage of different categories of elements in the model (states, transitions, conditions in transition guards, MC/DC coverage).

To the best of our knowledge, the only research works that address automated test generation for SCADE or LUSTRE programs is the work proposed in [60]. This work introduces a set of coverage criteria for LUSTRE and SCADE programs, defined over the graph of operators in the programs, and an automated tool that builds test suites that maximize these coverage criteria. The performance of the test generator is assessed by measuring the mutation analysis [61].

The above approach, however, differs in aim and scope from ours. Our approach systematically analyzes the C code that corresponds to the SCADE programs, while the approach of [60] does not consider the generated C code. The authors of [60] propose dedicated coverage measures, specific for synchronous dataflow programming languages, while we aim at covering all execution paths in the programs.

An interesting tool is RT-Tester [62, 63], which is used in industry to perform V&V activities for avionic, automotive and railway systems: it starts from a concrete test model describing the expected behaviour of the system under test, renders the models into a set of expressions in propositional logic, and then solves the formulas with a SMT solver to generate test cases. Bounded model checkers, like CBMC, take a similar approach [64]. They represent programs with boolean formulas, which they then check for satisfiability by using a SAT solver, to generate test cases as counterexamples of verification properties. In the future, we aim to compare with these approaches.

## 6 Conclusions

The development of safety-critical software must ensure with a high degree of confidence software programs that behave correctly in all operating conditions. To this end, automated software testing can assist in verifying the programs more thoroughly, more quickly, and at a lower cost than traditional, manual testing techniques. In this paper, we studied the viability of an automated test generation approach based on symbolic execution, specifically tailored on the characteristics of a programming language for safety-critical software systems. We instantiated the proposed approach with the tool TECS, a test generator for programs written the SCADE language. The case study that we reported in this paper indicates that the proposed approach was able to successfully produce test suites that achieve a high model coverage and assist in identifying faults for the considered safety-critical programs in SCADE, while keeping the test generation

effort under control.

We envision many opportunities for future research on the topic. We plan to extend the experimental assessment by considering further case studies. On one hand, we aim at assessing the scalability of the proposed approach through the analysis of components with growing complexity. On the other hand, we would like to investigate the possibility of extending our approach to safety-critical software developed in programming languages other than SCADE. We also plan to extend the evaluation of TECS by assessing the fault detection ability of the generated test suites, e.g. by exploiting a mutation framework for SCADE [61].

Lastly, the test cases generated by TECS currently contain assertion checks that are usable for regression testing only, but in the future we would like to integrate TECS with a component for generating general oracles. Automatic oracle generation is an open research problem, and we are currently studying how to extend techniques to automatically generate oracles from software annotations [65] so that the oracles are generated from the software requirements specification documents.

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