Automated Requirements-Based Testing of Black-Box Reactive Systems

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Abstract

We present a new approach to conformance testing of black-box reactive systems. We consider system specifications written as linear temporal logic formulas to generate tests as sequences of input/output pairs: inputs are extracted from the Büchi automata corresponding to the specifications, and outputs are obtained by feeding the inputs to the systems. Conformance is checked by comparing input/output sequences with automata traces to detect violations of the specifications. We consider several criteria for extracting tests and for stopping generation, and we compare them experimentally using both indicators of coverage and error-detection. The results show that our methodology can generate test suites with good system coverage and error-detection capability.

1 Introduction

We are concerned with the problem of checking whether a reactive system — which we can execute, but for which we have no internal representation — conforms to a set of requirements provided as temporal logic formulas. This problem arises in a variety of contexts, e.g., when a system is developed by integrating commercial off-the-shelf (COTS) components \cite{20}. In these scenarios, techniques such as model checking \cite{4} or (white-box) model-based testing \cite{28} are ruled out. Also, classical black-box techniques like random testing, equivalence partitioning or boundary analysis \cite{11} either do not take into account the specification or require manual effort to assemble meaningful test suites. Techniques aimed at automated test generation for black-box reactive systems relying on formal models of the specifications have been explored —
see, e.g., [19, 5, 18, 26, 17] — and they seem more promising than classical techniques when both efficiency of test generation and effectiveness in covering the specification are considered. Runtime verification [9] techniques can be seen as a form of oracle-based testing [10]: each test is executed on the system implementation and the test oracle, i.e., the monitor in runtime verification jargon, observes the system and checks whether its executions are behaviors allowed by the specification or not. Following this stream of research, a technique based on the use of monitors as test oracles is proposed in [3]. Their approach can test for safety properties (“something bad will never happen”), but it does not deal with liveness properties (“something good will happen infinitely often”). While liveness properties are not amenable to monitoring on finite executions, their proper subclass of co-safety properties (“something good will happen”) consists of formulas that can be monitored on finite traces and that we wish to consider when testing a system for conformance.

Our approach is inspired by [3], but aims to deal with a more general class of properties. Our methodology is based on a visit of the Büchi automaton corresponding to the requirements. The visit starts from the initial state of the automaton and generates a sequence of input values with which the black-box system is fed to obtain a corresponding sequence of output values. We check such input/output sequence against the automaton, i.e., we check whether there exists at least one state in the automaton that can be reached along the sequence. If there is no such state, then the system is not conformant to the requirements and the sequence provides a counterexample. Otherwise, we can continue the generation of the sequence by iterating the above steps until either (i) an acceptance state of the automaton is reached with a sequence of length at least $k_{\text{min}}$ or (ii) an acceptance state cannot be reached with a sequence of length at most $k_{\text{max}}$, where $k_{\text{min}}$ and $k_{\text{max}}$ are two parameters such that $k_{\text{min}} < k_{\text{max}}$. Multiple tests can be obtained by iterating this procedure until all the reachable transitions have been visited at least once.

We evaluate our approach in three different experimental settings. In the first one we consider benchmarks taken from the LTL Track of the 2018 edition of the Reactive Synthesis Competition (SYNTCOMP 2018)\(^1\) and we compare our approach with the one described in [3]. In the second setting we use the Adaptive Cruise Control (ACC) prototype implemented in [2] and we compare the tests generated by our approach with those generated with a model-based generation strategy. In the third setting we test the model of a robotic arm controller in order to evaluate our approach on a large set of requirements coming from an industry-grade prototype. In the two former settings we use a mix of fault-injection [15] and mutation analysis [1] in order to compare different approaches. In the third setting we inject faults manually. The results we obtained with our experiments show that our approach can outperform the one in [3] by finding more induced faults. Furthermore, generating tests based on the specification can be as effective as approaches based on the system model, discovering almost the same number of faults. Finally, our approach can be effective in finding faults.

\(^1\)http://www.syntcomp.org/
in small-to-medium sized industry-grade systems.

The rest of the paper is structured as follows. In Section 2 we present some basic notation and definitions. In Section 3 we describe our framework for test case generation of black-box system. Finally, in Section 4 we show experimental results and we conclude the paper in Section 5 with some remarks and an agenda for future work.

2 Preliminaries and Related Work

In this Section we recall the basic concepts used trough the paper. First, we present some basic definitions, followed by syntax and semantics of Linear Temporal Logic (LTL). Then we provide a short introduction to $\omega$-regular grammars and languages and we conclude the section by presenting related work.

2.1 Non Deterministic Büchi Automata

Definition 1 (Non Deterministic Büchi Automata). A non deterministic Büchi Automata (NBA) $A$ is a tuple $A = (Q, \Sigma, \delta, q_0, F)$ where:

- $Q$ is a finite set of states,
- $\Sigma$ is an alphabet,
- $\delta : Q \times \Sigma \rightarrow 2^Q$ is a transition function
- $q_0 \in Q$ is the initial state
- $F \subseteq Q$ is a set of accept states, called acceptance set.

Let $\Sigma^\omega$ denote the set of all infinite words over the alphabet $\Sigma$.

Definition 2 (Run). A run for an infinite word $\sigma = A_0A_1A_2... \in \Sigma^\omega$ denotes an infinite sequence $\varrho = q_0q_1q_2...$ of states in $A$ such that $q_0 \in Q_0$ and $q_{i+1} = \delta(q_i, A_i)$ for $i \geq 0$, and $\forall A_i, A_i \in \Sigma$.

Notice that each run $\varrho$ in a NBA induces a corresponding word $\sigma \in \Sigma^\omega$.

Definition 3 (Accepting run). A run $\varrho$ is accepting if there exist $q_i \in F$ such that $q_i$ occurs infinitely many times in $\varrho$.

Figure 1 (top), shows a NBA where $Q=\{0, 1, 2, 3, 4, 5, 6\}$, $\Sigma=2^{AP}$, $AP=\{p_0, p_1\}$, $q_0=0$, and $F=\{1, 3, 5\}$. Throughout the paper we make use of propositional logic formulae as a shorthand notation for the transitions of NBAs. For instance, a label $a \lor b$ on an edge from a state $q$ to a state $p$, represents three transitions from $q$ to $p$: one for the symbol $\{a\}$, one for the symbol $\{b\}$, and one for the symbol $\{a,b\}$. 

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2.2 LTL syntax and semantics

Linear temporal logic (LTL) [25] formulae consist of atomic propositions, Boolean operators, and temporal operators. The syntax of a LTL formula $\phi$ is given as follows:

$$\phi = \top | \bot | a | \neg \phi_1 | \phi_1 \lor \phi_2 | X \phi_1 | \phi_1 U \phi_2 | (\phi)$$

where $a \in AP$, $\phi, \phi_1, \phi_2$ are LTL formulae, $X$ is the “next” operator and $U$ is the “until” operator. In the following, unless specified otherwise using parentheses, unary operators have higher precedence than binary operators. We also write $\overline{\phi}$ to denote $\neg \phi$.

Informally, the semantics of an LTL formula $\phi$ can be defined over the language that contains all infinite words over the alphabet $2^{AP}$. More precisely:

**Definition 4** (Set of words over $2^{AP}$). Given a set of atomic propositions $AP$, $(2^{AP})^\omega$ denotes the set of words that arise from the infinite concatenation of symbols from the alphabet $(2^{AP})$. Each word is defined as $\sigma = A_0 A_1 A_2 \ldots \in (2^{AP})^\omega$, where each $A_i$ is a set over $AP$, i.e. $A_i \in 2^{AP}$. 

Figure 1: A state-based Büchi automaton (top), the corresponding monitor (bottom-left) and a Mealy machine (bottom-right). We write $\overline{p_i}$ to denote $\neg p_i$. 

[Diagram of state-based Büchi automaton, monitor, and Mealy machine]
In the following, for $\sigma = A_0A_1A_2 \ldots \in (2^{AP})^\omega$, $\sigma[j \ldots] = A_jA_{j+1} \ldots \in (2^{AP})^\omega$ is the suffix of $\sigma$ starting in the $(j+1)$st symbol $A_j$.

**Definition 5** (LTL semantics over words). Let $\phi$ be an LTL formula over the set $AP$ and let $\sigma = A_0A_1A_2 \ldots$ be an infinite word over $(2^{AP})$. We define the relation “$\models$” between $\sigma$ and $\phi$ as the smallest relation with the following properties:

1. $\sigma \models \text{true}$
2. $\sigma \models a$ iff $a \in A_0$
3. $\sigma \models \phi_1 \land \phi_2$ iff $\sigma \models \phi_1$ and $\sigma \models \phi_2$
4. $\sigma \models \neg \phi$ iff $\sigma \not\models \phi$
5. $\sigma \models X \phi$ iff $\sigma[1\ldots] = A_1A_2A_3 \models \phi$
6. $\sigma \models \phi_1 U \phi_2$ iff $\exists j \geq 0$ such that $\sigma[j\ldots] = A_jA_{j+1} \ldots \models \phi_2$ and $\sigma[i\ldots] \models \phi_1 \quad \forall 0 \leq i < j$

We consider other Boolean connectives like “$\land$” and “$\rightarrow$” with the usual meaning, while we introduce $\Diamond \phi$ (“eventually”) to denote $\top U \phi$ and $\Box \phi$ (“always”) to denote $\neg \Diamond \neg \phi$.

**Definition 6** (Accepted Words for a LTL formula). We also define the set of accepted Words of a LTL formula $\phi$ as the set containing all the infinite word $\sigma$ over $2^{AP}$ that satisfy the property $\phi$, i.e.

$$\text{Words}(\phi) = \{\sigma \in 2^{AP} \mid \sigma \models \phi\}$$

**Theorem 1** (Constructing an NBAs for an LTL formula [4]). For any LTL formula $\phi$ (over $AP$) there exists an NBA $A_\phi$ with $\text{Words}(\phi) = L_\omega(A_\phi)$.

**Example 1.** Figure 1 (top), shows a NBA obtained from the formula $p_0 \leftrightarrow (X \Box p_1 \lor \Diamond p_1)$ where $AP = \{p_0, p_1\}$. The NBA is obtained using SPOT [13].

**Definition 7** (Mealy machine). A Mealy machine is a tuple $M = (S, s_0, I, O, \delta)$ where:

- $S$ is a finite set of states,
- $s_0 \in S$ is the start state
- $I$ is a set of symbols called input alphabet,
- $O$ is a set of symbols called output alphabet,
- $\delta : S \times I \rightarrow S \times O$ is a transition function mapping pairs of states and input symbols to the corresponding pairs of states and output symbols

\[\text{Using the command line } \text{ltl2tgba -B -f "p0 <-> (X G p1 | ! F p1)"}\]
In other words, a Mealy machine is a finite-state machine whose output values are determined by its current state and the current inputs.

**Example 2.** Figure 1 (bottom-right) shows a Mealy machine obtained by using STRIX [23] on the formula

$$p_0 \leftrightarrow (X \Box p_1 \lor \Diamond \overline{p_1})$$

where $S = \{0,1,2\}$, $s_0 = 0$, $I = \{p_0\}$ and $O = \{p_1\}$.

### 2.3 Monitor

A monitor is an automaton supposed to follow the execution of a system and move accordingly. An error is detected when the monitor cannot move, i.e., the system has performed some action, or reached some state that it was not meant to be.

**Definition 8 (Monitor).** A monitor $M$ is a tuple $M = (Q, \Sigma, \delta, q_0)$ where:

- $Q$ is a finite set of states,
- $\Sigma$ is an alphabet,
- $\delta : Q \times \Sigma \rightarrow 2^Q$ is a transition function
- $q_0 \in Q$ is the initial state

**Example 3.** Figure 1 (bottom-left) shows a monitor obtained using SPOT [13] for the formula

$$p_0 \leftrightarrow (X \Box p_1 \lor \Diamond \overline{p_1})$$

where $Q = \{0,1,2,3\}$, $\Sigma = 2^{\mathcal{AP}}$, $\mathcal{AP} = \{p_0, p_1\}$, and $q_0 = 0$.

### 2.4 Related Work

The research most closely related to ours is presented in [3] where the authors describe a methodology for online testing of Java classes. Their key technique is to exploit a monitor derived from LTL specifications to check conformance of the system to stated requirements, with a focus on safety properties. In order to compare this methodology with our approach, we reimplemented the idea presented in [3], making it applicable to any black-box system and not just Java classes. Another work related to ours is presented in [19] where the authors describe a methodology for specification based testing of black-box systems. They assume that the specification of the system is given as a non-blocking input/output timed automaton, and the system itself — whose model need not to be known — is also a timed automaton. The two main differences between their methodology and ours are (i) the capability of dealing with real-time requirements and (ii) the form of the specification: ours is “declarative”, in the

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3Fired with command line ltl2tgba -MD -f “p0 <-> (X G (p1 | ! p1))”.

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form of a set of LTL requirements, whereas theirs is “operational” in the form of an automaton. We thus incur into one additional step, i.e., extracting an automaton from the requirements, after which the two methodologies proceed in a similar way. However, given the different form and expressivity of the requirements, a direct comparison is not easily feasible, and might be even misleading. More recently in [5], another approach based on timed automata to specify input signals constraints has been proposed. Also this approach bears some similarity with ours and with that of [19], but in our opinion it is not directly comparable, at least in the settings that we consider for our experimental analysis.

Other research which is closely related to ours appears in a series of papers [27, 30, 29] where the authors present a test-case generation methodology that (i) translates LTL requirements into Generalized Büchi Automata, (ii) builds trap properties from them — using different criteria — and (iii) performs model checking of negated trap properties against the system model in order to extract test cases. The main difference with our work is that such methodology relies on a model of the system under testing, a model that must be verified against the system specification. Failing to do so, may generate conflicting tests, i.e., a test which fulfills a requirement, and violates another. To the extent of our knowledge there is no other recent work on formally-grounded methods for requirement based testing, while there is some not-so-recent work mentioning conformance testing to specification, such as, for example [18, 26, 17]. However, in these works specifications are mostly “operational” in the form, e.g., of finite state machines and thus a direct comparison with our methodology is not possible.

3 Automatic Test Case Generation from LTL specification

In order to test black-box systems, our approach adopts the workflow presented in Figure 2. We assume that the specification is composed of a list of LTL formulas, the declaration of the set $I$ of input propositions, and the set $O$ of output propositions such that $I \cup O = AP$ and $I \cap O = \emptyset$. The “Test Generator”
pipeline in Figure 2 has the goal to produce a set of valid tests to execute on the system under test (SUT). The pipeline comprises four components:

- **Parser** reads the input specification, creates the intermediate data structures and builds the conjunction of requirements.
- **Automata Builder** builds a Büchi or equivalent automaton representation of the input specification.
- **Input Generator** chooses which inputs to execute on the SUT.
- **Test Oracle** evaluates the output produced by the SUT and checks if it satisfies the specifications.

**Testing Environment** is responsible for orchestrating the interaction between the components. It queries **Input Generator** for new inputs to test and it executes them on the SUT. **Testing Environment** collects the output and passes it to **Test Oracle** for evaluation. If the test is complete, **Testing Environment** stores the final verdict and resets the environment to start a new test. Moreover, the **Test Oracle** provides to the **Input Generator** the set of possible states in which the automaton can currently be, given the executed trace. In the following, we present each step of our implementation in more detail.

### 3.1 Requirements and Automata Processing

The input of the test generator algorithm is a set \( R = \{ \phi_1, \ldots, \phi_n \} \) of LTL formulas along with the list of input and output variables. The parser reads the input formulas as a conjunction \( \Phi = \phi_1 \land \cdots \land \phi_n \) to build the corresponding automaton. We rely on **spot**\(^{[13]} \) to perform the construction of the Büchi automaton represented as a directed graph. Before test generation starts, we preprocess the automaton by expanding the edges where **spot** groups different equivalent assignments to move from one state another, to obtain exactly one assignment for each edge. During preprocessing, variables are omitted if they are not relevant for a particular transition, e.g., if the transition is enabled independently from their value. In such cases, we set the input variables to false by default, while we leave the outputs unchanged. This is because we want to have a fully defined and deterministic input, but we do not want to impose additional constraints that are not specified by the requirements on the outputs. Other choices are possible; for example, one could set the undefined inputs randomly or could copy the value of such variables from previous assignments, if any.

### 3.2 Test Oracle

The aim of the test oracle is to decide if a trace \( \tau \), composed of input and output variables, is correct with respect to the given LTL specification \( \Phi \). A more permissive check, often considered for runtime monitoring, consists in verifying that \( \tau \) is a valid prefix of the language \( \text{Words}(\Phi) \). This can be done
by checking that there exists a run induced by \( \tau \) on the automaton \( A_\Phi \), or, equivalently, using monitors. This kind of check is useful to identify violations of safety properties, but it is ineffective for liveness ones, even for the co-safety subclass. For example, we cannot detect violations of the formula \( \phi = \Diamond a \) with a monitor, because every prefix is valid as long as the proposition \( a \) becomes true eventually. In order to solve this issue, a number of different LTL semantics for finite traces have been proposed, such as FLTL[21], LTL\( ^+ \)[14], LTL\( _3 \)[7] and LTL-RV[8]. In [6] the authors propose a counting semantics making predictions based on the number of steps necessary to witness the satisfaction or violation of a formula. Evaluations under such semantics can range from a 2-valued verdict – namely True (\( \top \)) or False (\( \bot \)) – to a 5-value one; Presumably True (\( \top P \)), Inconclusive (?), Presumably False (\( \bot P \)) and False (\( \bot \)). The choice of the semantics defines the specific kind of conformance to the specification adopted and implemented by the test oracle. In the following, we rely on the FLTL semantics, formalized below in Definition 9 — for a discussion of different semantics, we refer the reader to [8].

**Definition 9.** Given a finite word (or trace) \( \tau \) of length \( n \) and an FLTL formula \( \phi \), \( \tau(= \tau, 0) \) satisfies \( \phi \), denoted as \( \tau \models \phi \), under the following conditions (s.t. \( 0 \leq i < n \)):

\[
\begin{align*}
\tau, i &\models p \in AP \quad \text{iff} \quad a \in \tau[i] \\
\tau, i &\models \neg \phi \quad \text{iff} \quad \tau, i \not\models \phi \\
\tau, i &\models \phi_1 \land \phi_2 \quad \text{iff} \quad \tau, i \models \phi_1 \quad \text{and} \quad \tau, i \models \phi_2 \\
\tau, i &\models X \phi \quad \text{iff} \quad \tau, i+1 \models \phi \\
\tau, i &\models N \phi \quad \text{iff} \quad i = n \quad \text{or} \quad \tau, i+1 \models \phi \\
\tau, i &\models \phi_1 \mathcal{U} \phi_2 \quad \text{iff} \quad \exists j < n. (\tau, j \models \phi_2 \quad \text{and} \quad \forall i \leq m < j. (\tau, m \models \phi_1)) \\
\tau, i &\models \Diamond \phi \quad \text{iff} \quad \exists j < n. (\tau, j \models \phi) \\
\tau, i &\models \Box \phi \quad \text{iff} \quad \forall i \leq j < n. (\tau, j \models \phi)
\end{align*}
\]

Regarding the boolean operators, FLTL semantics coincides with the standard LTL semantics on infinite words. However, with temporal operators, such as \( X \) and \( U \), there is a difference concerning the maximum length of the word. In particular, the semantics distinguishes between a strong next operator \( X \), which require a next time step to exists, and a weak version \( N \), which it is always satisfied at the last step of a trace. In our requirements, however, we only make use of the strong variant. In our approach, the FLTL oracle is implemented on an automaton and traces are checked directly on the generated Büchi Automata. We posit that every trace \( \tau \) ending in an acceptance state \( q^* \) of the Automata \( A_\Phi \), also satisfies the formula \( \Phi \) from which the automaton is built.

### 3.3 Input Generator

The main idea behind the generation of input sequences for testing the SUT consists in exploring different paths of the automaton \( A_\Phi \) that represents the specification. Given a choice of (i) an exploration strategy to prioritize paths and (ii) a termination condition to end the search, we obtain our algorithm
Guided Depth First Search (GDFS) presented in 1. As the name suggests, it is a variant of the classical depth-first search algorithm on directed graphs.

\textbf{Algorithm 1} Guided Depth First Search
\begin{algorithmic}[1]
\Function{GDFS}{\(A\Phi, k_{\text{min}}, k_{\text{max}}, \text{oracle}, \text{env}\)}
\State \text{visitCounter} \leftarrow \text{EMPTYMAP( } )
\For{\(e \in A\Phi\text{.OUTGOINGEDGES}(A\Phi\text{.initState})\)}
\State \text{visitCounter}[e] \leftarrow 0
\EndFor
\While{\(\exists e \in \text{visitCounter}.(\text{visitCounter}[e] == 0)\)}
\State \(\tau \leftarrow \{\}\)
\State \(s_c \leftarrow A\Phi\text{.initState}\)
\State \text{env\text{.RESET}( } )
\While{\text{oracle\text{.VALIDPREFIX}(\(\tau\))} \land |\(\tau\)| < \(k_{\text{max}}\)}
\For{\(e \in A\Phi\text{.OUTGOINGEDGES}(s_c) \land e \notin \text{visitCounter}\)}
\State \text{visitCounter}[e] \leftarrow 0
\EndFor
\State \(e \leftarrow \text{SELECTNEXTEDGE}(A\Phi, s_c, \text{visitCounter})\)
\State \(i \leftarrow \text{GETINPUT}(e)\)
\For{\(e \in A\Phi\text{.OUTGOINGEDGES}(s_c) \land \text{GETINPUT}(e) == i\)}
\State \text{visitCounter}[e] \leftarrow \text{visitCounter}[e] + 1
\EndFor
\State \(o \leftarrow \text{env\text{.PERFORMACTION}(i)}\)
\State \(s_c \leftarrow \text{GETSUCCESSOR}(A\Phi, s_c, i \cup o)\)
\State \(\tau\text{.APPEND}(i \cup o)\)
\If{\(|\tau| \geq k_{\text{min}} \land s_c \in A\Phi\text{.acceptanceStates}\)}
\State \text{break}
\EndIf
\EndWhile
\State \(\text{res} \leftarrow \text{oracle\text{.EVALUATE}(\(\tau\)})\)
\State \text{env\text{.ADDPTEST}(\(\tau, \text{res}\))}
\EndWhile
\EndFunction
\end{algorithmic}

The algorithm takes as input the automaton \(A\Phi\), the interval \(k_{\text{min}}\) and \(k_{\text{max}}\), i.e., the minimum and the maximum length of each trace, the \text{oracle} object and the environment \text{env} object. The algorithm starts with the initialization of the visitCounter map, that counts how many times an edge has been explored (lines 2-5). Notice that only the outgoing edges from the initial state are initialized, while the other ones are incrementally added during the exploration (lines 11 - 13). The algorithm terminates when all the edges in visitCounter have been visited at least once. At the beginning of each test, the trace \(\tau\) is initialized to an empty word and the current state \(s_c\) is initialized to the initial state of the automaton (lines 7-8). Then the environment is reset to start at the initial state (line 9). The test is computed by iteratively choosing an edge (line 14), extracting the input on its label (line 15), executing it on the SUT by means
of the $env$ object (line 19) and using the output to choose the successor state, if any, and to build the trace $\tau$ (lines 20 - 21). The function `selectNextEdge` chooses the next state to execute by selecting the edge with less visits so far. In case of multiple edges with the same score, it sorts them with an heuristics that takes into account the distance from the nearest acceptance state and the degree of the target state. Moreover, the `visitCounter` is updated after each choice (lines 16 - 18) by increasing the counter of all edges leaving $s_c$ that present the input $i$. This is a small optimization to reduce the number of steps necessary to terminate, because many edges could produce the same input but expect different accepted outputs. From an input point of view, these edges are equivalent, but only one of them will be traversed, depending on the produced output. Termination of a test occurs exactly when one of the following three cases is true: (i) $\tau$ is no more a valid prefix of $L(A_\Phi)$ and therefore the test failed; (ii) the length $\tau$ reached the maximum length $k_{\text{max}}$; (iii) the length of $\tau$ is greater than $k_{\text{min}}$ and the exploration reached an acceptance state. At the end of each test, the oracle gives its final verdict and the result is stored in the $env$ object (lines 26 - 27).

4 Experimental Analysis

We present the results of three experiments\textsuperscript{4} involving the framework previously introduced. In the first one, we aim to assess the quality of the generated test suite involving a set of benchmarks borrowed by the LTL Track of the Reactive Synthesis Competition 2018\textsuperscript{5} (SYNTCOMP 2018). The second experiment aims to compare the effectiveness of our approach with respect to model-based strategies; in order to do that, we consider the use case of an Adaptive Cruise Control System made available in [2] and we compare our algorithm with state-of-the-art model-based approaches when it comes to spotting erroneous mutants. Finally, our last experiment aims to evaluate the scalability of our approach in a real world use case. So, we consider a set of requirements from the design of an embedded controller for a robotic manipulator used in the context of the EU project CERBERO\textsuperscript{6} [22, 24]. The experiments described in the following ran on a workstation equipped with an Intel Xeon E31245 @ 3.30GHz CPU and 32GB RAM running Lubuntu 18.10 64bits. For all the experiments, we granted a time limit of 600 CPU seconds (10 minutes) and a memory limit of 30GBs.

4.1 Syntcomp Benchmarks

The set of benchmarks we consider is the one provided for the LTL Track of the Reactive Synthesis Competition 2018. We first translate the TLSF [16] specifications into equivalent LTL ones accepted by our tool. Note that we do not use SyFCo, a tool for manipulating and transforming TSLF specifications in

\textsuperscript{4}All benchmarks are available at https://gitlab.sagelab.it/sage/benchmarks-tests
\textsuperscript{5}http://www.syntcomp.org/
\textsuperscript{6}http://cerbero-h2020.eu
other existing specification formats for synthesis, because we handle ASSUME formulae in a different way. In particular, SyFCo would translate ASSUME formulae as a precondition (left-hand side of an implication) and the ASSERT and GUARANTEE formulae as postconditions (right-hand side of an implication). Therefore, if an ASSUME formula is violated, the system is not required to satisfy the given requirements. This behavior would lead to many useless tests, because whenever an assumption is falsified during the test execution, the specification would be trivially satisfied and no constraint would be enforced on the output. In order to solve this problem, we require the ASSUME part to be satisfied together with the ASSERT and GUARANTEE part, i.e., we replace implication with conjunction. We refer the reader to [16] for more details on the standard translation from TLSF to LTL. We exclude benchmarks whose output assignments appear in the ASSUME part of the specification. This is because, as explained before, we require the assumptions to hold during the execution of the test, but assumptions containing outputs can always be falsified, thus failing the test. We synthesize Mealy machines for the specifications with Strix [23], the winner of the SYNTCOMP 2018 competition, and we exclude benchmarks for which Strix times out in 600 CPU seconds. For each synthesized Mealy machine, we compute 100 mutants randomly applying one of the following rules:

- change the target state of a random transition to a different one;
- flip the output value of a variable on a random transition, namely setting it to false if it was true and vice-versa.

We apply only one mutation per mutant because the synthesized models are usually small in size and one variation is often enough to expose a violation of the specification. However, some of the resulting mutants may still be correct with respect to the corresponding specification. At the end of this process we have 128 different benchmarks, each of those with 100 mutants. In the experiment, we compare the results obtained with 5 different algorithms. GDFS-1, GDFS-3 and GDFS-5 are the algorithm described in Section 3 with $k_{\text{min}}$ set to 1, 3 and 5, respectively. For comparison purpose, we also re-implemented, – and generalized to fit our framework – the algorithm presented in [3]. Briefly, the algorithm traverses the monitor automaton of the specification during the test execution, and stops when a coverage criteria is fulfilled. A test is concluded either when an objective is reached or when the maximum length $k_{\text{max}}$ of the trace is reached. In [3] two strategies are proposed, namely Random Walk (RW) and Guided Walk (GW) and we implemented and tested both of them. As for the coverage criteria, we implemented what they call Atomic Proposition Coverage (APC), i.e., each atomic proposition on each transition of the monitor must be covered. For each algorithm we set $k_{\text{max}}$ equal to 100 and we stop the execution as soon as a test fails and the mutant is killed. Notice that 600 CPU seconds are allotted to each benchmark, including automata processing and evaluation of all mutants.

Figure 3 (left) shows the number of mutants killed per benchmark by each
Figure 3: Total amount of mutants killed (left) and average number of steps (right) computed by the considered algorithms in the set of SYNTCOMP 2018 benchmarks.

algorithm, ranging from 0 to 100. Figure 3 (right) shows the average number of steps executed, namely the sum of the length of each test, averaged over the mutants. In both charts, the abscissa represents the number of benchmarks, while the ordinate shows the number of mutants killed (left) and the number of steps executed (right). Notice that, since the results of RW and GW can vary due to non-deterministic behaviors, we execute the test 3 times and we report the median value as reference for these two algorithms. The results reveal that GDFS-5 clearly outperform all the other algorithms in terms of total amount of mutants killed, and that the number of executed steps is only slightly higher than GDFS-1 and GDFS-3. However, only for two benchmarks all the 100 mutants have been killed. Moreover, in 25 cases it did not kill any mutant, 15 of which due to timeouts. Regarding RW and GW, they both revealed totally ineffective for 73 of the 129 benchmarks, although only 2 timeouts occurred. However, looking at Figure 3 (right) we notice that in 59 of these benchmarks, the two algorithms did not perform any testing at all. This phenomenon is due to the nature of the benchmarks involved, where the specification only contains liveness properties and the monitor is a single state automaton accepting all prefixes.

4.2 Adaptive Cruise Control

In our second experiment we consider the Adaptive Cruise Control (ACC) prototype implemented in [2]. The ACC system adjusts the current velocity of the vehicle towards a target cruise velocity defined by driver. If the vehicle gets too close to the forward vehicle, the ACC system must adjust the current distance between the two and maintain a certain safety distance. Additionally, the driver can intervene by: (1) activating the system via an ACC button; (2) deactivating the system via the ACC button; and (3) deactivating the system by braking or accelerating the car. The authors of [2] also generated test cases from LTL requirements using three different requirements coverage criteria: re-
Table 1: Experimental results on the ACC use case.

|                      | RC | AC | UFC | GDFS-1 | GDFS-3 | GDFS-5 |
|----------------------|----|----|-----|--------|--------|--------|
| Number of Test Cases | 6  | 7  | 18  | 26     | 4912   | 2597   |
| Branch Coverage (%)  | 78.3| 78.3| 86.7| 45.0   | 70.0   | 71.7   |
| Number of Killed Mutants | 488 | 488 | 488 | 414     | 480    | 480    |
| Killed Mutants (%)   | 93.1| 93.1| 93.1| 79.0    | 91.6   | 91.6   |

requirements coverage (RC), antecedent coverage (AC), and unique first cause coverage (UFC). Tests are generated with a model-based generation strategy: trap-properties are built from requirements, and a counterexample is produced with a model checker. The algorithms are evaluated with 524 mutants of the correct implementation.

The goal of the experiment here described is to compare the performance of our algorithm with respect to model-based techniques that make explicit use of a model to generate test cases. We modified slightly the set of requirements, reducing numerical comparisons and enums (available in the NuSMV [12] models used in [2]) to boolean variables. This is a mere syntactic variation to represent LTL formulae in the default syntax as described in Section 2.2. The resulting specification is composed of 12 requirements, 6 input and 10 output variables. The results are depicted in Table 1. In order to ease the comparison with the model-based approach, we also report the results from [2].

The results show that the GDFS algorithm performances are comparable to the model-based algorithms, with a difference of only 8 mutants (1.5% of the total) for $k_{min}$ equal 3 or 5, at the expense of many more tests. Notice however that the test generation and execution is still quite small; it takes about 1 second to run GDFS-1, 11 seconds for GDFS-3 and 5 seconds for GDFS-5. Moreover, the whole test suite is executed only if all tests succeed, but if a failure is detected it can terminate much earlier. In the case of GDFS-5, for example, the average number of tests executed per mutant is 329, much lower than the test suite size (2597). However, despite the large test suite, GDFS reaches a lower branch coverage than the model-based counterparts, stopping at 71.7%. Also notice that, in this context, with all requirements being safety properties, the RW algorithm described in the previous experiment performs well, achieving similar results to GDFS-5 (although with some variation due to randomness). These results show that the black-box testing with the framework presented in Section 3 can be almost as effective as model-based techniques, where more manual work is required to model the system. A final remark on the $k_{min}$ and $k_{max}$ parameters of the GDFS algorithm is in order. As shown in Table 1, $k_{min}$ plays an important role in the test suite size and performance. In our experience, the longer the test, the more the automaton is covered and the less transitions close to the initial state are repeated. Similarly, also $k_{max}$ can influence a test suite size and performance: an excessively small value could lead to some false positive tests, while an excessively large value could produce unnecessarily long tests before declaring them failed. However, the generated test suite depends not only on the algorithm and the specification, but also on the SUT behavior. The optimal values of such parameters is context dependent, and may require
some fine tuning.

4.3 Robotic Manipulator

Our last experiment considers a set of requirements from the design of an embedded controller for a robotic manipulator. The controller should direct a properly initialized robotic arm — and related vision system — to look for an object placed in a given position and move to such position in order to grab the object; once grabbed, the object has to be moved and released into the bucket without touching it. The robot must stop also in the case of an unintended collision with other objects or with the robot itself — collisions can be detected using torque estimation from current sensors placed in the joints. Finally, if a general alarm is detected, e.g., by the interaction with a human supervisor, the robot must stop as soon as possible. The manipulator is a 4 degrees-of-freedom Trossen Robotics WidowX arm equipped with a gripper. The design of the embedded controller is part of the activities related to the “Self-Healing System for Planetary Exploration” use case in the context of the EU project CERBERO. In this case the specification is composed of 31 requirements, 3 inputs and 11 outputs. The SUT is implemented as an smv model. With GDFS-5 ($k_{\text{min}} = 5$ and $k_{\text{max}} = 30$), we obtain 1441 tests and a total of 12867 steps executed in 1171 seconds. At each step, NuSMV [12] is called in order to determine the evolution of the system. Then, we manually inject faults by removing some constraints in the guards (forcing the system to evolve from one state to another) or by modifying value assignments of some variables. At the end, we obtain 10 different NuSMV faulty models. We show the results of this analysis in Table 2. First, we report that a failed test has been detected in all considered cases. Looking at the Table, we can observe that, for each bugged system, a small number of tests is necessary to discover the failure. Therefore, in most cases, it is not necessary to perform a complete exploration of the automaton and an early stopping strategy can save substantial time when debugging an application.

5 Conclusions

In this paper, we have described a new approach to conformance testing of black-box reactive systems. We evaluated our approach across three different experimental settings. In the first setting we synthesized a set of benchmarks taken from the SYNTCOMP 2018 competition and we showed that our approach is better at finding mutants than (a generalization of) two different algorithms presented in [3]. In the second setting, we showed that our approach compares favorably with state-of-the-art model-based techniques. Finally, in the third setting we tested a controller for a robotic manipulator modeled in smv and we showed that our approach is able to find some manually injected faults. As future work, we plan to (i) extend the framework with more test oracles and

\footnote{http://www.trossenrobotics.com/widowxrobotarm.}
Table 2: Fault-Injection results on the robotic manipulator use case.

| # Injection | # Tests | # Steps | Time(s) |
|-------------|---------|---------|---------|
| 1           | 1       | 2       | 7.64    |
| 2           | 2       | 14      | 8.61    |
| 3           | 2       | 14      | 8.74    |
| 4           | 1       | 2       | 7.75    |
| 5           | 1       | 7       | 8.15    |
| 6           | 4       | 25      | 8.61    |
| 7           | 56      | 502     | 25.23   |
| 8           | 1       | 3       | 8.15    |
| 9           | 1       | 6       | 7.84    |
| 10          | 2       | 10      | 8.17    |

exploration strategies and (ii) increase the input language expressiveness with the addition of numerical constraints. The implementation of our approach is freely available in the SpecPro\(^8\) Java library.

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\(^8\)https://gitlab.sagelab.it/sage/SpecPro
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