Test Generation for SystemC designs by interlaced Greybox Fuzzing and Concolic Execution

MUKTA DEBNATH∗, Indian Statistical Institute, India
ANIMESH BASAK CHOWDHURY∗, New York University, USA
DEBASRI SAHA, A.K. Chowdhury School of IT, University of Calcutta, India
SUSMITA SUR-KOLAY, Indian Statistical Institute, India

Recent success in high-level synthesis (HLS) has enabled designing complex hardware with better abstraction and configurability in high-level languages (e.g., SystemC/C++) compared to low-level register-transfer level (RTL) languages. Nevertheless, verification and testing HLS designs are challenging and arduous due to their object oriented nature and inherent concurrency. Test engineers aim to generate qualitative test-cases satisfying various code coverage metrics to ensure minimal presence of bugs in a design. Recent works have demonstrated the success of software testing techniques such as greybox fuzzing and concolic execution to obtain better coverage on SystemC designs. However, each of these techniques is time inefficient which obstructs achieving the desired coverage in shorter time-span. We propose a hybrid approach: interleave greybox fuzzing and concolic execution in a systematic manner, thereby reinforcing both the engines by exchanging intermediate test vectors to alleviate the individual inefficiency of the techniques. We evaluate our framework on a wide spectrum of SystemC benchmarks and show that our technique outperforms existing state-of-the-art methods in terms of number of test cases, branch-coverage and runtime.

Keywords: SystemC, High-level Synthesis, Greybox fuzzing, Symbolic Execution, Concolic Execution, Code Coverage

1 INTRODUCTION

In recent times, hardware designers are increasingly adopting high-level design frameworks like SystemC, synthesizable C/C++ for modular design of complex hardware and ease of automated design-space exploration. SystemC has become the de-facto standard for early-stage development of hardware designs which paves the foundation of a complex design architecture. Thus, it is crucial to verify and test the design thoroughly to eliminate a range of functional incorrectness and hardware bugs. Detecting functional and security bugs at early stage design development remains an important problem to solve.

A SystemC design provides cycle-accurate behavioural modeling of a given specification. Therefore, testing SystemC design focuses more on functional level correctness, inconsistency in specifications and unknown (possibly buggy) behaviour rather than defects arising from low-level hardware. The cost of detecting bugs at a later design stage is too high; increasing the overall design cost. Therefore, hardware engineers prefer to test logic functionality of designs at early design stage and check for hardware defects during later design stages. This motivates verification and test engineers to develop a good automated test generation framework for detecting bugs at high level designs.

Verification and testing SystemC designs (and, in general high level designs) for bug detection have a rich literature [10, 20–24, 36]. Prior works adopt two mainstream approaches to tackle the problem: 1) formal techniques, and 2) simulation-based techniques. Formal techniques used methods such as model checking [10, 16, 20] and symbolic execution [14, 36] to explore the state-space of the design. Contrary to that, simulation-based techniques use black-box, white-box [17, 18] and grey-box [35, 38] approaches to test the design thoroughly. There are plethora of works that have critically identified

∗Equal contribution while at Indian Statistical Institute

Authors’ addresses: Mukta Debnath, mukta.tj@isical.ac.in, Indian Statistical Institute, Kolkata, India; Animesh Basak Chowdhury, abc586@nyu.edu, New York University, New York, USA; Debasi Saha, debasri_cu@yahoo.in, A.K. Chowdhury School of IT, University of Calcutta, Kolkata, India; Susmita Sur-Kolay, ssk@isical.ac.in, Indian Statistical Institute, Kolkata, India.
the issues like *scalability* and *exhaustive testing* in each of these techniques and addressed them by proposing hybrid approach: *concolic testing*. A very recent work [30] have applied concolic testing alleviating the problem of scalability arising from symbolic execution. Although the approach is quite promising, we ask two important questions which are yet unaddressed in current literature:

1. Concolic testing relies heavily on initial test-cases. A low initial branch coverage will result in more time consumption by concolic engine to cover the entire design state-space. Therefore, how can one generate better quality test-cases (in a minimalistic time frame) such that concolic execution focus only on "hard-to-reach" state of design?

2. Guided fuzzing-based techniques (e.g. [37, 38]) can quickly explore the design space however fails to penetrate deeper as it get stuck in complex branch conditions. Thus, how can one alleviate this problem in fuzzing?

In this work, we aim to accelerate design state-space exploration by interleaving two state-of-the-art techniques: Greybox fuzzing and Concolic execution (note that our focus is on test-case generation and branch coverage but not on testing per se, thus we use the term concolic execution instead of concolic testing). We propose a hybrid test generation framework: *GreyConE* which address existing pitfalls by interchanging test-cases back and forth between these techniques and reinforces each other. We leverage the power of greybox fuzzing by quickly covering "easy-to-reach" states in a design and pass on "hard-to-reach" state to concolic engine. In short, we make the following contributions in this work:

1. We developed *GreyConE*: an end-to-end automated test generation framework combining the best of both worlds i.e. greybox fuzzing and concolic execution.

2. *GreyConE* outperforms state-of-the-art Greybox fuzzer (AFL [38]) and concolic test generation (S2E [15]) in terms of branch coverage achieved and runtime speedup.

The rest of the paper is organized as follows: Section 2 outlines the background and prior related works. In Section 3, we present our proposed framework and show the efficacy of results in Section 4. Section 6 concludes our work.

2 BACKGROUND

2.1 Testcase generation for SystemC Designs

SystemC is the most popular system level modeling language used in electronic design and verification flow industry. It enables integration and verification of highly complex systems that include arbiters, buses and legacy RTL. HLS synthesizable C++/SystemC code is one fifth the number of lines of code compared to RTL which makes it easier to write and debug. The simulation speed is typically between 30-500X faster than RTL allowing much more verification and consuming far less compute resources [2]. SystemC verification is meant to assure that SystemC designs implement the specifications correctly. As verification is an extremely critical phase for successful products, ensuring the correctness of high-level SystemC designs, namely SystemC verification is crucial, especially for safety critical systems, as undetected errors will propagate and become very costly. Innovative approaches to SystemC Verification are welcomed in the industries. Generating quality test-cases that produce high code coverage metrics are in huge demand by verification and test engineers.

2.2 Related Works

SystemC verification using symbolic execution and concolic execution has been explored recently in works like SESC [30] and CTSC [28]. SESC adapted symbolic execution on SystemC designs with significant code coverage but limited
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To only a subset of SystemC features. Subsequent work like CTSC covers almost all semantics of SystemC language but could not improve efficacy in terms of performance and scalability compared to SESC. Also, both the work depends on the availability of initial stimuli for the symbolic engine. Another work from the same authors, SCT-HTD [27], generates test cases for behavioral SystemC designs using concolic testing with an additional objective of trojan detection. Fuzz testing has recently been explored for testing RTL designs [13, 25], although not much used to test SystemC designs. In [26] Le et al has proposed a fuzzing-based framework, AFL-SHT, for test generation to detect hardware trojans in high level SystemC designs. The primary limitation of both these works, SCT-HTD and AFL-SHT, is that they require a golden model for each SystemC DUV. There is also a recent shifts that focus on SystemC TLM verification [19, 23]. TLM provides more abstraction, however, TLM makes very little or no use of signals and clocks. Thus TLM cannot replace or wipe out SystemC at all.

2.3 Lightweight Instrumentation

Instrumentation involves adding extra code to an application for monitoring some program behavior and obtaining useful information about the target program. Such code instrumentation can be performed by automated injection of control flow statements on every conditional statement. This insertion is done automatically during the abstract syntax tree (AST) generation phase of the compiler. The instrumentation of the design is done only once and does not affect the original functionality of the design. This kind of code transformation and analysis is done using clang [3] and LLVM [6] compiler. The instrumentation increases the visibility of the program and fetch coverage information for test engines.

2.4 Greybox fuzzing

Fuzz testing is a well known technique in software domain for detecting bugs. Greybox fuzzing [11] generates interesting test vectors using evolutionary algorithms on instrumented design executable. Instrumentation injects markers in the design code which post compilation and execution can track whether a test-case has reached the marker location. A fitness function is used in order to evaluate the quality of a test-vector. Typically, greybox fuzzing is used to improve branch-pair coverage of the design, therefore the codes are annotated at every basic block. A test-vector is regarded as interesting, if it reaches a previously unexplored basic block, or hits it for a unique number of times. The fuzz engine maintains a history-table for every basic block covered so far, and retains interesting test vectors for further mutation/crossover. The test generation process completes once the used-defined coverage goal is achieved. Popular coverage-guided greybox fuzzing (CGF) engine like AFL [38] have been able to detect countless hidden vulnerabilities in well-tested softwares.

2.5 Symbolic and Concolic Execution

Symbolic execution interprets programs by assigning symbolic rather than concrete data to program input. When the execution reaches a branch whose condition involves symbolic values, the symbolic engine forks the program state, such that each path has its private version of the program state. In this way, the engine can explore both branches independently and in parallel. The hierarchy of program states forms an execution tree, as in Figure 1b). Execution is performed by a symbolic execution engine, which maintains for each explored control flow path: (i) a first-order Boolean formula that describes the conditions satisfied by the branches taken along that path, and (ii) a symbolic memory store that maps variables to symbolic expressions or values. Branch execution updates the formula, while assignments update the symbolic store [7]. A model checker, typically based on a satisfiability modulo theories (SMT) solver [8], is eventually used to verify whether there are any violations of the property along each explored path and if
```c
int foo(int i, int j){
    // i and j symbolic variables
    int x = 0, y = 0, z;
    z = 2*j;
    if(z == i){
        if(j < 5){
            x = -2; y = 2;
        } else {
            x = 2; y = 2;
        }
    } else {
        x = 2; y = 2;
    }
    return 0;
}
```

(a)

![Fig. 1. (a) Example code snippet. (b) Symbolic and concolic Execution flow](image)

the path itself is realizable, i.e., if its formula can be satisfied by some assignment of concrete values to the program’s symbolic arguments. Performing fully symbolic execution hampers due to the inherent state space explosion problem of symbolic execution. The size of the execution tree grows exponentially with the number of conditional statements, an effect called path explosion. To ease the path explosion problem concolic execution has emerged in research.

Sometimes, symbolic execution may get stuck even at the start of the execution and have a hard time reaching deep paths. To alleviate this problem the program is executed with concrete values to give a hint to the execution engine about which path to follow first. **Concolic execution** executes a program concretely and collects symbolic path conditions along the way dictated by the concrete inputs. After the concrete run, constraints at each branch point are negated and then solved to generate a new test case that would explore a path not covered by the concrete input. The path constraints generated in concolic execution have reduced the number of clauses and variables, thereby making it easier for solvers and can penetrate deep into complex program checks. Concolic execution allows the program under analysis to run to completion without getting lost in state space.

In Figure 1b) a), we have put a simple code snippet that depicts the behavior of concolic execution. In concolic execution, the program inputs are treated as both concrete and symbolic. The inputs to the program, $i$ and $j$ that depend on conditions are treated as symbolic inputs with assignment of symbolic values, $i = a$ and $j = b$. An initial execution trace is obtained by assigning concrete values to the program inputs ($i = 2$, $j = 1$). Symbolic constraints are collected along the execution path guided by concrete inputs, forking the side branches. The concrete run trace is highlighted in green arrows in the Figure 1b b). The alternative paths to be explored symbolically are shown with black arrows. Circle denotes the branch points. At each branch point the constraints are negated and solved to generate new test cases. On successful execution, the program will exit by assigning appropriate values to the output variables $x$ and $y$. KLEE [12] and S2E [15] are famous symbolic execution engine built upon LLVM infrastructure. S2E provides the illusion of full symbolic execution, but actually switches between symbolic and concrete execution. Driller [34], CUTE [32] follows such approach based on concolic execution.
GreyConE test generation framework

Fig. 2. GreyConE test generation framework. Fuzz engine is fed with initial test-cases. As coverage improvement ceases in fuzz engine, Concolic engine starts execution with fuzz generated test cases. Fuzz engine and Concolic engine execute sequentially to penetrate deep into hard-to-satisfy conditional checks of programs. The Trojan Detector checks for trojan whenever GreyConE generates a new test-case.

Algorithm 1: FUZZER(DUT_{ins-exec}, T_{Initial})

Data: Instrumented Design Under Test DUT_{ins-exec}, User provided test-inputs T_{Initial}, User defined time bound time_{cut-off}

Result: T_{fuzzed} ⊲ Interesting test-inputs queue

T_{fuzzed} ← T_{Initial} ⊲ Initialization of the AFL’s test-inputs queue

while time ≤ time_{cut-off} do
    for τ ∈ T_{fuzzed} do
        K ← CALCULATE_ENERGY(τ)
        for i ∈ {1, 2, ..., K} do
            τ’ ← MUTATE-SEED(τ)
            if IS-INTERESTING(DUT_{ins-exec}, τ’) then
                T_{fuzzed} ← T_{fuzzed} ∪ τ’
                end
        end
    end

return T_{fuzzed}

3 GREYCONE FRAMEWORK

We present the workflow of GreyConE in Fig. 2. The GreyConE framework consists of four components: 1) Design Instrumentation unit 2) Greybox fuzz engine, 3) Concolic execution engine, and 4) Coverage evaluator.
3.1 Design Instrumentation and Binary Generation

As shown in Figure 2, high-level designs predominantly written in SystemC/C++ are initially passed through a static analysis tool, LLVM, to generate intermediate representation (IR) in the form of LLVM bitcode. This IR is fed to the clang compiler which performs lightweight instrumentation of the IR by translating each basic block with instrumented code and generates the instrumented LLVM bitcode or the executable IP. S2E works on such LLVM bitcode generated by the clang compiler. A coverage guided greybox fuzzer like AFL also works on such instrumented executable. Instrumentation of code helps the fuzzer to track the execution flow exercised by an input and determine whether the input covers a new part of the program that has not been executed before. Here we use afl-clang-fast, which is based on clang [3], a front end compiler for programming languages like C, C++, SystemC, among others for code instrumentation and binary generation. Thus, our framework does not require any translation of the SystemC designs, and can work directly on binaries.

3.2 Greybox Fuzzing by AFL

AFL captures basic block transitions and coarse branch -taken hit counts into a bitmap by lightweight instrumentation of the DUT. It then leverages genetic algorithm to guide mutations. A test case that triggers new program behaviors is collected into a seed queue of American fuzzy lop (AFL) which is used as seed file to mutate. In algorithm 1, we outline the overall flow of Greybox fuzzing by AFL. At first, we provide the high-level instrumented executable $DUT_{ins-exe}$ and a user-provided test-set $T_{initial}$ to the fuzzing framework. The $CALCULATE-ENERGY$ function assigns energy to the initial seed $T_{initial}$ on the basis of external features of the test case like the execution time, bitmap coverage, depth of the test case in terms of fuzzing hierarchy. A test case that is fast, covers more branches and has more depth, is given more energy. AFL then decides the number of random fuzzing iterations for that test case. AFL uses $T_{initial}$ to perform operations like deterministic mutations and havoc mutations to generate newer test-cases with the help of the $MUTATE-SEED$ function. AFL uses branch-pair as a fitness metric to determine the quality of test-input. For each branch-pair, AFL maintains a hash-table entry to record the number of times it is hit. The $IS-INTERESTING$ function checks whether the mutated test case is interesting or not. AFL considers a test-input to be interesting, if it covers a new-branch pair not hit so far, or has hit a branch-pair unique number of times compared to past observations. Interesting test-inputs are retained to form the next candidates for fuzzing. The algorithm terminates when either no more interesting test cases can be found or the user-defined $time_{cut-off}$ expires. AFL maintains all interesting test-inputs in the queue $T_{fuzzed}$.

3.3 Concolic Execution by S2E

In our work, we use S2E as our symbolic execution engine for test-generation. S2E has two main components: 1) A virtual machine based on QEMU [9] and 2) a symbolic execution engine based on KLEE. S2E have the elasticity to switch back and forth between concrete execution and symbolic execution. S2E consists of an automated path explorer and a modular path analyzers. The explorer drives the target system down all execution paths of interest and the analyzer checks the properties of each such explored path. We provide the same instrumented $DUT_{ins-exe}$ executable and a set of test-cases $T_{initial}$ to the symbolic engine as given to the fuzz engine. The $CONC-EXEC$ execute the $DUT_{ins-exe}$ with all test-cases $T_{initial}$ generating concrete execution traces. symbolic executer (S2E) maintains an execution tree $DUT_{execTree}$ and identifies all conditional nodes’ true and/or false edges not covered by $T_{initial}$. The $COND-PREDICATE$ construct the path constraints for the uncovered edge of condition, forks new thread and invoke
Algorithm 2: CONCOL-EXEC(DUT_ins-exec,T_initial)

| Data: DUT_ins-exec, T_initial | Result: T_concolic
|-------------------------------|--------------------------
| DUTexecTree ← ϕ             | ̸→ Set of test-cases generated by the concolic engine
| for τ ∈ T_initial do         | ̸→ Execution tree for DUT
|     P_trace ← CONC-EXEC(DUT_ins-exec,τ) | P_trace ← DUTexecTree ∪ P_trace
| end                          | Perform symbolic execution steps targeting uncovered conditional statements
| for uncovered cond c ∈ DUTexecTree do |
|     pc ← COND-PREDICATE(c)   | T_concolic ← T_concolic ∪ t_i
|     t_i ← CONSTRAINT-SOLVER(pc) |
| end                          |
| return T_concolic            |

SAT-solver (CONSTRAINT-SOLVER) to generate the test-cases. The final test-cases reported by S2E ideally should cover all conditions of DUTexecTree. The test case queue T_concolic holds all the test cases generated by the concolic engine. Algorithm 2 outlines this approach. S2E also allows a portion of code to be considered for pure symbolic execution and rest for concolic execution in an interleaved fashion an approach called Selective Symbolic Execution. Such an approach enables S2E to focus on interesting and hard-to-reach code regions with symbolic inputs. In that case we specify the interested symbolic inputs using S2E’s s2e_make_symbolic() function in the design itself and then invoke the concolic engine. We will elaborate with an example in Section 4.

3.4 Fuzzing and Concolic Execution of SystemC Designs:

We interleave greybox fuzzing and concolic execution in an algorithmic manner, extenuating the problems associated with standalone techniques. Path selection heuristic of symbolic engines may not always know which execution path to choose so that execution can go deeper. It may even get stuck at the beginning of an execution and have hard times reaching deep paths. Symbolic execution engines like S2E have support for alternating back and forth between symbolic execution and concrete execution which allows the program to run with concrete seed inputs. We exploit this property of the symbolic engine and obtain such seed inputs by performing random fuzzing of the DUT. The seeds generated by the fuzzer are assigned priorities based on new basic block coverage. For each seed the symbolic engine forks a new state and runs the binary using that seed to obtain a concrete execution trace. Symbolic execution exercises this trace symbolically to generate new test cases. If there is no more new seed, it forks a new state which is fully symbolic. To cope with the path explosion problem of the symbolic engine, we fixed the time given to S2E for execution. S2E generated test cases are fed back to the fuzz engine which again generates interesting seed inputs for the DUT. This process continues till a terminating condition is satisfied. As shown in Fig. 2, we first perform lightweight instrumentation on all conditional statements of design-under-test (DUT) and generate an instrumented executable. We start our fuzz-engine(FUZZER) with a set of initial test-cases. The fuzz-engine generate interesting test-cases using genetic algorithm and explore various paths in the design. Once branch-pair coverage cease over a user-defined time period time_threshold, concolic engine(CONCOL-EXEC) is invoked for unseen path exploration. The CONCOL-EXEC identifies uncovered conditions in DUTexecTree and forks new threads for symbolic execution on such conditions using depth-first search strategy. We use fuzzed test-cases for concolic engine to generate new testcases satisfying complex conditional statements. To avoid scalability bottleneck, we limit its runtime of concolic execution engine by time_threshold, that monitors the time elapsed since the last test case generated. If no new test case is generated over a period of this threshold time, we again invoke the fuzz engine. Concolic execution generated
Algorithm 3: GreyConE (DUTins-exec. T_initial, tb time_cut-off, time_threshold_f, time_threshold_c)

Data: Instrumented Design Under Test (DUTins-exec), Initial test-inputs (T_initial), (tb) is the design’s testbench, Time limit (time_cut-off), Threshold time limit for coverage improvement by Fuzzer (time_threshold_f), Threshold time limit for new test case generation by concolic engine (time_threshold_c).

Result: T GreyConE

Function InvokeConcolic(DUTexecTree, i):

1. time_testgen ← 0
   
   [Monitor time elapsed since last test case generated]

2. for uncovered cond c ∈ DUTexecTree do
   
   3. p_c ← COND-PREDICATE(c)
   
   4. t_new ← CONSTRAINT-SOLVER(p_c)
   
   5. Invoke Coverage Evaluator with T GreyConE (algorithm 4)
   
   6. if time_testgen > time_threshold then
      
      7. break
   
8. i ← 1
   
8. T GreyConE ← T_initial
   
8. time_coverage ← 0
   
8. while time ≤ time_cut-off do
   
   9. for τ ∈ T GreyConE do
      
   10. K ← CALCULATE_ENERGY(τ)
      
   11. for j ∈ {1, 2, ..., K} do
      
   12. τ' ← MUTATE-SEED(τ)
      
   13. if IS-INTERESTING(DUTins-exec, τ') then
      
   14. T GreyConE ← T GreyConE ⊃ τ'
      
   15. Invoke Coverage Evaluator with T GreyConE (algorithm 4)
      
   16. if time_coverage > time_threshold then
      
   17. InvokeConcolic(DUTexecTree, i)  
      
   18. if time > time_cut-off then
      
   19. return T GreyConE
   
20. end
   
21. end
   
22. end
   
23. end
   
24. coverage_info ← ConSIMULATOR(DUTexec-exec, th, T GreyConE)
25. coverageGreyConE = reportCoverage(coverage_info)
26. return (T GreyConE, coverageGreyConE)

Testcases are fed back to fuzzer allowing scalable exploration of deeper program segments. This process continues when the user-defined coverage goal is achieved or the testing process is run for a pre-defined time_cut-off. Whenever a new test case is generated with either the fuzz engine or the concolic engine, it is added to T GreyConE, the test case queue for the framework, and the coverage evaluator is invoked with T GreyConE. If the target coverage tgt_cov is achieved, then our test engine displays the result of the testing process with the code coverage report and stops. Otherwise we run GreyConE for a pre-defined time_cut-off and report coverage metrics with the generated test-cases. We formally present our test-generation approach in algorithm 3.
3.5 Generating Coverage Report:

We have developed an automation script to simulate the SystemC designs, iterating over all the generated test cases using a testbench for each design and report code coverage from the execution. We wrap automation around gcov [4] along with all the test cases generated by our framework to fetch data for the overall code coverage achieved in the form of lcov [5] HTML report. Manual interpretation of cumulative lcov report provides data on any uncovered branches. Coverage analyzers like afl-cov [1] which generate gcov code coverage results for a targeted binary, give the provision to check coverage of any specific lines or function of code. As depicted in algorithm 4, the coverage evaluator is fed with the DUT executable compiled with coverage support DUTexe−cov, the testbench for the design tb and the GreyConE generated test-cases. The CovSIMULATOR invokes the SystemC library that provides predefined structures and simulation kernel for simulation of SystemC designs and simulates the design with the GreyConE generated test cases. It generates the coverage information in coverageinfo from the execution traces obtained by running the SystemC design with the generated test-cases. The overall code coverage report is generated from this coverageinfo by the reportCoverage function. The final coverage report is recorded in coverageGreyConE and returned.

In this work we do not perform assertion insertions or assertion based validation but some designs from the SCBench with existing assertions are considered. Assertions in the form of conditional statements are inserted in certain critical sections of the code. Symbolic engines like S2E provide the facility to the underlying solver to look for assertions and generate test cases that target the execution towards those assertions. Such assertions give the confidence for designs to be error free after replaying with the generated test cases that trigger the assertions. Such test cases could identify bugs or unusual behavior in the designs.

**Example:** In Listing 1 we show the code segment for the design MD5C (message digest algorithm to generate cryptographic hash function). We observe that, before reaching the final branch of design at line 7, there is an assert statement at line 5 for correctness checking. Such statements induce the symbolic engine to produce counter examples that lead to the trigger of these assertions. S2E also provides the s2e_assert() function for validation purposes that checks the equivalence of two functions over the same path.

```
Listing 1. Example of assertion usage in SystemC design
1  // Main computational loop
2  while (1) {
3      m_inputLen = i_inputLen.read();
4      /* Usage of assertion */
5      assert( m_inputLen <= MD5C_INPUT_BUFSIZE );
6      final = i_final.read();
7      if ( final == true ) {
8        MD5Final();
9      }
```

```
Algorithm 4: COV-EVALUATOR (DUTexe−cov, tb, TGreyConE)

| Data: DUTexe−cov, tb, TGreyConE |
|----------------------------------|
| coverageinfo ← CovSIMULATOR(DUTexe−cov, tb, TGreyConE) |
| coverageGreyConE = reportCoverage(coverageinfo) |
| if coverageGreyConE ≥ tgtcov then |
|     Target coverage achieved |
|     break |
| end |
| return (TGreyConE, coverageGreyConE) |
```


4 EXPERIMENTAL SETUP AND DESIGN

4.1 Experimental setup

We implement GreyConE using state-of-the-art software testing tools: AFL (v2.52b) [38] for greybox fuzzing and S2E [15] to perform concolic execution. For robust coverage measurements, we cross-validated our results using coverage measurement tools: namely afl-cov-0.6.1 [1], lcov-1.13 [5], and gcov-7.5.0 [4]. Experiments are performed on 64-bit linux machine having i5 processor and 16 GB RAM clocked at 3.20 GHz.

4.2 Benchmark characteristics

We evaluate GreyConE on the wide spectrum of available SystemC benchmarks: SCBench[29] and S2CBench[31]. These designs are selected from a wide variety of application domains covering many open-source hardware designs. The benchmarks considered have diverse characterization: ADPCM, FFT, IDCT (all image processing cores), AES, MD5C (cryptographic cores), Quick_sort (data manipulation), Decimation (filters) and UART (communication protocols).

4.3 Design of experiments

We evaluate the efficacy of GreyConE in two aspects: 1) Coverage improvement and 2) Run-time speedup. We compare our results with state-of-the-art testing techniques: fuzz-testing based approach (AFL) and concolic execution (S2E). We now describe our experimental setup:

**Baseline 1 (Fuzz testing):** We run AFL on SystemC benchmarks using default algorithmic setting for AFL. Initial seed inputs are randomly generated.

**Baseline 2 (Concolic execution):** Like baseline 1, we run S2E on SystemC benchmarks having default configurations. Randomly generated concrete seed inputs are provided to S2E.

**GreyConE:** We run GreyConE on SystemC benchmarks starting with randomly generated input test-cases. We set $t_{threshold_f} = 5s$ and $t_{threshold_c} = 10s$ as timing threshold for fuzz-engine and concolic engine respectively. These are user defined configurable parameters.

For our experiments, we set a run-time limit of two hours and compared branch coverage achieved by baseline methods and GreyConE. We now discuss the performance of GreyConE in terms of branch-coverage improvement and run-time speedup.

5 RESULTS AND EVALUATION

GreyConE invokes fuzz-engine and concolic engine interchangeably. We have annotated each phase of run incrementally. For e.g. $fuzz_k$ denotes fuzz-engine is in $k^{th}$ execution phase. To show the effectiveness of GreyConE, we present branch coverage achieved in each phase along with number of test-cases generated in Table 1. In Table 2, we report the number of test-cases generated; achievable branch coverage within the pre-defined time-limit (i.e. 2 hours) and the earliest time taken to reach that coverage. We compare our results with AFL [38] and S2E [15] as these are open-sourced implementations. Due to unavailability of implementation of SESC [30] and CTSC [28], we used S2E [15] to reproduce results and demonstrate the performance of concolic execution on SystemC designs by adopting necessary changes.

1) **Coverage achieved by GreyConE:** We reported GreyConE’s coverage result in Table 1 achieved in each execution phase. We show the branch coverage achieved by each of the test generation techniques. Higher branch coverage indicates higher probability of test-cases detecting bugs hidden in deeper program segments. We observe that for certain designs, GreyConE does have to invoke concolic engine at all. This indicates that the benchmarks do not have complex
Table 1. GreyConE’s performance during fuzzing and concolic execution

| Benchmarks | LOC | Testcases | Branch cov. (%) | Time(in s) |
|------------|-----|-----------|-----------------|------------|
|            |     |           | fuzz1 | conc1 | fuzz2 |            | fuzz1 | conc1 | fuzz2 |            | fuzz1 | conc1 | fuzz2 |
| ADPCM      | 270 | 5         | 6     | -     | 93.3 | 99.9      | 100   | -     | 39    | -         |
| AES        | 429 | 3         | 4     | 4     | 79.2 | 83.3      | 91.7  | 76    | 29    | 51        |
| FFT_fixed  | 334 | 3         | 3     | -     | 81.2 | 96.9      | -     | 29    | 137   | -         |
| IDCT       | 450 | 62        | 137   | -     | 64.8 | 100       | -     | 7     | 222   | -         |
| MD5C       | 467 | 5         | 3     | 2     | 87.5 | 90.6      | 100   | 9     | 34    | 7         |
| Filter_FIR | 176 | 3         | 2     | 7     | 76.8 | 87.5      | 93.8  | 7     | 23    | 37        |
| Interpolation | 231 | 44     | -     | -     | 100  | -         | -     | 3     | -     |            |
| Decimation | 422 | 3         | 2     | -     | 96.8 | 100       | -     | 12    | 22    | -         |
| Kasumi     | 415 | 31        | 23    | -     | 93.3 | 100       | -     | 10    | 46    | -         |
| UART       | 160 | 2         | 15    | 4     | 81.2 | 84.1      | 88.5  | 334   | 136   | 248       |
| Quick_sort | 204 | 7         | -     | -     | 100  | -         | -     | 14    | -     | -         |

“branching” conditions where fuzzer could get stuck. For every designs, GreyConE achieves maximum possible coverage post one call to concolic engine. Here, we claim GreyConE achieved “maximum” possible coverage as we independently validated that the portion of “uncovered” branches are unreachable codes(AES, FFT_fixed, Filter_FIR and UART). We compare the branch coverage obtained by GreyConE with other techniques in Table 2. We see GreyConE outperforms

Table 2. GreyConE’s performance compared to AFL [38] and S2E [15] (Time-limit: Two hours)

| Benchmarks | LOC | Test-cases generated | Branch cov. (%) | Time taken (s) |
|------------|-----|----------------------|----------------|---------------|
|            |     | AFL | S2E | GreyConE | AFL | S2E | GreyConE | AFL | S2E | GreyConE |
| ADPCM      | 270 | 30 | 21 | 11 | 96.9 | 94.4 | 100 | 124 | 374 | 48   |
| AES        | 429 | 23 | 8  | 11 | 88.7 | 82.4 | 91.7 | 1745 | 314 | 156 |
| FFT_fixed  | 334 | 7  | 46 | 6  | 96.9 | 96.9 | 96.9 | 1215 | 2051 | 166 |
| IDCT       | 450 | 110| 146| 199| 74.1 | 84.2 | 100 | 29  | 422 | 229 |
| MD5C       | 467 | 11 | 45 | 10 | 90.6 | 70  | 100 | 1329| 1214| 50   |
| Filter_FIR | 176 | 11 | 36 | 12 | 93.8 | 93.8 | 93.8 | 551 | 89  | 67   |
| Interpolation | 231 | 44 | 5  | 44 | 100  | 100  | 100 | 3   | 37  | 3    |
| Decimation | 422 | 4  | 5  | 5  | 100  | 100  | 100 | 372 | 1065| 34   |
| Kasumi     | 415 | 60 | 76 | 54 | 100  | 100  | 100 | 58  | 233 | 56   |
| UART       | 160 | 4  | 54 | 21 | 81.2 | 85.7 | 88.5 | 334 | 730 | 718  |
| Quick_sort | 204 | 7  | 13 | 7  | 100  | 100  | 100 | 14  | 248 | 14   |
baseline techniques AFL and S2E in terms of coverage achieved. In Figure 3 we show the coverage improvement of GreyConE over AFL and S2E. As illustrated, the test cases produced by GreyConE significantly improves the branch coverage by 3%-25.9% compared to AFL and 2.8%-30% compared to S2E within two hours time limit. Figure 5 provide a detailed coverage analysis over the entire time period of two hours.

Listing 2. IDCT code with compound conditional checks

```c
/* No Zero Column Test */
if (inptr[1]==0 & inptr[2]==0 & inptr[3]==0 &
     inptr[4]==0 & inptr[5]==0 & inptr[6]==0 &
     inptr[7]==0) { //Branch 1
workspace_t dcval = DEQUANTIZE(inptr[0], quantptr[0]) << PASS1_BITS;
...
wsstr[DCTSIZE*7] = dcval;
wsstr++; // advance pointers to next column
continue; }
/* No Zero Row Test */
if (wsstr[1]==0 & wsstr[2]==0 & wsstr[3]==0 &
     wsstr[4]==0 & wsstr[5]==0 & wsstr[6]==0 &
     wsstr[7]==0) { //Branch 2
sc_uint<8> dcval = range_limit[(int) DESCALE((INT32) wsstr[0], PASS1_BITS+3) & RANGE_MASK];
outptr[0] = dcval;
...
outptr[7] = dcval;
wscr = DCTSIZE;//advance pointer to next row
```

Listing 3. Making IDCT-coefficient input symbolic

```c
/* sc_int<16> inptr[];

Comment the scanning of concrete data from file input
for ( int j = 0; j < 8; j++ ) {
    //inptr[j] = input_coef.read(); //reading input coefficient for IDCT
    s2e_make_symbolic(inptr, sizeof(inptr), "inptr"); //making the inputs symbolic for symbolic run
    ....
}
```

Case Study with IDCT: Inverse DCT (Discrete Cosine Transform) program expresses a finite sequence of data points in terms of a sum of cosine functions of different frequencies. It takes an idct-input file and an idct-coefficient file as arguments to the program binary. In Listing 2 we put a portion of code snippet for IDCT that checks the presence of zero in the column of the IDCT input-coefficient and presence of zero in the workspace input, using compound conditional statements in Branch 1(line 2) and Branch 2(line 12). While running IDCT with GreyConE, at fuzz1 phase, a branch coverage of 64.8% was obtained quickly by the fuzzer but got stuck crossing the tthreshold time without improving coverage. From the lcov coverage report we found that the fuzz engine could not generate test cases satisfying the checks inptr[3] = 0, inptr[4] = 0 and inptr[7] = 0 of Branch 1 (line 2,3,4) and could not satisfy any of the conditions at Branch 2. So GreyConE switches to con1 phase. At con1 phase, the concolic engine could only reach a branch coverage of 72.2% satisfying all conditions at Branch 2 spending 68 seconds, after which it could not generate any new test cases within tthreshold time. So GreyConE switched to fuzz2 phase. But the fuzzer got stuck reaching 77.8% branch coverage,
Test Generation for SystemC designs by interlaced Greybox Fuzzing and Concolic Execution

Fig. 3. Coverage improvement by GreyConE

satisfying the check $inptr[7] = 0$. of Branch 1 (line 4) unable to explore any new path that improves coverage. This continuous switching of phases by GreyConE give rise to scalability bottleneck. Thus to avoid such costly execution, we switch to selective symbolic execution mode at $con_1$ phase and make the changes highlighted in Listing 3.

We run IDCT with one of its input argument $idct-input$ in concolic mode, tracing the program along the same path taken by the fuzzer generated seed. The other input to the IDCT design $idct-coefficient$ is made symbolic. This enables GreyConE to explore all possible execution paths through the program that correspond to all possible inputs at $con_1$ without crossing the threshold time limit of concolic engine. Thus, although GreyConE spends longer time at $con_1$ phase but end up successfully covering all the uncovered conditions of Branch 1 attaining 100% branch coverage with its generated test cases.

2) Analyzing run-time speedup: In our work, we measure the time taken to obtain best achievable coverage by baseline techniques and compare run-time speedup by GreyConE to achieve the same. From Figure 5, we observe that time taken to achieve a certain branch coverage is lower bounded by GreyConE compared to AFL and S2E.

In Figure 4 we show the run-time speedup of GreyConE over AFL and S2E for the designs where every technique has achieved the same branch coverage within the time-limit. As shown, GreyConE significantly accelerates to reach a certain branch coverage. The speed-up achieved by GreyConE are in line with our design approach: 1) GreyConE quickly identifies the region where fuzz engine gets stuck and invoke concolic engine to solve the complex conditions; 2) GreyConE avoids expensive path exploration by concolic execution by using fuzzer generated seeds leading to faster exploration and test-case generation.

3) Analyzing test-case quality: In Table 1, we present the number of test cases generated by GreyConE at each execution phase to reach the maximum branch coverage. GreyConE leverages S2E with fuzz generated test-cases to accelerate the coverage over a pre-defined time period. The fuzzer generated input seeds guide the symbolic engine to construct the execution tree along the execution path triggered by existing test-cases and generate new test cases reaching unexplored conditional statements. For a fair comparison with GreyConE, we report the number of test-cases
preserved by each technique until it reaches user-defined timeout (or, till the maximum coverage is achieved) in Table 2. A closer analysis reveals that number of testcases generated by GreyConE is same as AFL in cases where AFL as standalone was sufficient in reaching the target coverage without getting stuck for $t_{threshold_f}$. But, for cases where AFL crossed the $t_{threshold_f}$ to generate a new testcase that improves coverage, GreyConE invokes concolic engine for generating qualitative testcases quickly. Similarly when S2E gets stuck for $t_{threshold_f}$, GreyConE invokes the fuzz engine. Finally, GreyConE needs fewer testcases than both AFL and S2E indicating good quality test-case generation.

6 CONCLUSION

In this work, we have identified crucial challenges with state-of-the-art testing approaches for SystemC designs. We proposed GreyConE: an end-to-end test-generation framework penetrating into deeper program segments of SystemC designs. Our results show scalable generation of test cases with better branch branch coverage and accelerated design space exploration compared to state-of-the-art techniques. GreyConE has alleviated the drawbacks of fuzzing and concolic execution by algorithmically interleaving them. Future works include enhancing GreyConE to low-level netlist (RTL/gate-level) using tools like Verilator [33] and uncover hardware specific bugs in design.

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Fig. 5. Branch coverage obtained on SystemC designs while running GreyConE, S2E, AFL over a time period of two hours.

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