Test Suite Minimization of Evolving Software Systems: A Case Study

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Abstract: Test suite minimization ensures that an optimum set of test cases are selected to provide maximum coverage of requirements. In this paper, we discuss and evaluate techniques for test suite minimization of evolving software systems. As a case study, we have used an industrial tool, Static Code Analysis (SCAN) tool for Electronic Device Description Language (EDDL) as the System Under Test (SUT). We have used standard approaches including Greedy, Greedy Essential (GE) and Greedy Redundant Essential (GRE) for minimization of the test suite for a given set of requirements of the SUT. Further, we have proposed and implemented *k*-coverage variants of these approaches. The minimized test suite which is obtained as a result reduces testing effort and time during regression testing. The paper also addresses the need for choosing an appropriate level of granularity of requirements to efficiently cover all requirements. The paper demonstrates how fine grained requirements help in finding an optimal test suite to completely address the requirements and also help in detecting bugs in each version of the software. Finally, the results from different analyses have been presented and compared and it has been observed that GE heuristics performs the best (run time) under certain conditions.

1 INTRODUCTION

Testing is the process of executing a program with the intent of finding errors. It helps in reducing the maintenance cost of the software and accounts for the maximum percentage of effort among all phases of the software development life cycle. In an evolving software, with the introduction of new functionalities (progressive) and bug fixing (corrective), regression testing comes into the picture which ensures that changes do not affect the existing software. Fixing regression errors is much more complex than seeded errors (Böhme et al., 2013). Formal verification can guarantee the absence of errors, but requires clear specifications and is very effort intensive. Thus, in practice, regression testing is preferred (Böhme and Roychoudhury, 2014). New software development techniques like component and agile software development have led to a substantial increase in the complexity of regression testing (Yoo and Harman, 2012). Further, with the advent of Internet of Things, there has been a proliferation in embedded software, which needs to be tested against many non-functional requirements in addition to the functional requirements. This again adds up to the complexity of regression testing. Interaction with the non-deterministic physical environment also poses a big challenge to the testing of such systems (Banerjee et al., 2016).

In continuously evolving systems, whenever bugs in a previous version are fixed and the system is rebuilt, the naive solution is to run all the test cases which is very cumbersome and time consuming. As the software evolves, usually the size of the software and the number of test cases increase which inflate the testing effort and it becomes infeasible to run all the test cases. Thus, it becomes necessary to find the representative (minimal) set of test cases required to cover all requirements in an effective manner. As the software evolves, only the minimized test cases are checked instead of all existing test cases. This helps in reducing the testing time, which in turn reduces the overall time for software development.

Systems that are being designed, need to satisfy certain set of specified characteristic properties. Some tools may be designed to check if they satisfy these properties. One such effort has been the SCAN tool used for static code analysis of programs written in EDDL (Mohan and Jetley, 2018). The tool helps in

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debugging and issuing warnings for commonly occurring software errors in EDDL programs. For regression testing of the tool, it is important to find the minimal test cases from a given test suite to cover all its requirements. The input here is a set of programs (test cases), P; a set of patterns of errors to be captured (requirements), R; the system to be tested (the SCAN tool) and a mapping between P and R. The result of the minimal coverage analysis is a set of programs, $p \subseteq$ P, that are sufficient to cover all the requirements, $r \in$ R . It is useful to find p as in all the future corrective versions of the tool, testing p should be enough to cover all the requirements. We have adapted and implemented some of the approaches (Greedy, GE and GRE heuristics) of requirements coverage to perform a case study on the SCAN tool (Tallam and Gupta, 2006; Chen and Lau, 1996). From a reliability perspective, one could say that each property should be covered at least by two test cases, or k test cases for some k. To this effect, k-coverage variants of these heuristics have also been implemented. The value of k can be chosen based on the resources available in hand. The effectiveness of all these heuristics has been demonstrated and evaluated. It has been shown that if more fine grained requirements are considered, it leads to better coverage. We shall describe our approach and our experience in using such heuristics in the context of the SCAN tool (SUT).

The key contributions of this paper are: *(i)* application of Greedy, GE and GRE heuristics to an industrial project *(ii)* proposal of k-coverage variants of these heuristics *(iii)* comparison of all these heuristics on the project *(iv)* recommendation to use GE heuristics under certain conditions *(v)* fine grain the requirements and its impact on coverage.

The rest of the paper is structured as follows. Section 2 gives a background on EDDL, SCAN tool and various minimization approaches. The approaches used to find minimal cover for the case study are described in Section 3. Implementation and the analyses details are covered in Section 4. Comparison of the various approaches with respect to each analysis is done in Section 5. Finally, we conclude in Section 6 along with the future directions.

2 BACKGROUND

2.1 EDDL

Electronic Device Description Language (EDDL) is a structured and descriptive programming language for configuration and engineering of digital devices that conforms to the IEC 61804-3 standard. Since it is a text based language, it supports cross platform compatibility and it is independent of control platforms and operating systems. EDDL describes function blocks, device parameters with their dependencies, along with default and initial values of each device type. This helps in getting a clear picture of the device before it is actually present in the system. EDDL is derived from ANSI C and therefore supports interactive methods, domain-specific data structures and nesting among different sections. As EDDL supports multiple protocols and device types, it provides consistency and uniformity throughout the system and enables manufacturers to create a single engineering environment (IEC-61804-3, 2015).

2.2 SCAN Tool for EDDL

SCAN tool utilizes the concept of static code analysis to detect potential sources of run time errors in the control code at the compile time itself (Mohan and Jetley, 2018). It ensures compliance to good programming practices and coding guidelines. It is helpful as it identifies faults (which can cause system failures later) at an early stage of development. It can be used for other domain-specific languages that have similar structure and characteristics as EDDL (Mandal et al., 2018). It generates Abstract Syntax Tree (AST) and Control Flow Graph (CFG) for the control code with the help of a customized parser (Irony parser) (Irony-v1.0.0, 2018). AST is used to check syntactic and pattern based matching while CFG is used for interval domain based data flow analysis to compute range of all the variables in the code. The tool generates a *.csv* file that lists down the errors and warnings with detailed description, line number and severity level.

A sample EDDL code is shown in the code listing below. When this program is given as an input to the SCAN tool, it reports (in a *.csv* file) syntactic errors such as duplicate language definition on Line 3 and use of assignment instead of equals on Line 9. It also reports potential run time errors such as divide by zero and arithmetic overflow on Line 11.

```
 1  METHOD Method_Example
 2  {
*3      LABEL "Example|en|Sample";
 4      DEFINITION
 5      {
 6          int x, y, z;
 7          x=10;
 8          y=5;
*9          if(x=10)
 10         {
*11           z=x/(x-2*y);
 12         }
 13     }
 14 }
```

2.3 Minimization

Regression testing techniques can be classified into three major categories (Yoo and Harman, 2012):

1. Minimization: Identifies and eliminates redundant test cases from test suite.
2. Selection: Finds a subset of minimized test cases, required to test changes in the software.
3. Prioritization: Schedules execution order of test cases to increase early fault detection.

All of them are closely related to each other as they have similar aims, inputs and solutions.

Test suite minimization can be mapped to minimal set cover problem and is thus an NP complete problem. Therefore, most of the existing techniques are based on heuristics. Horgan and London (1992) applied linear programming to the minimization problem. Later, GE and GRE heuristics were applied which are essentially variations of the greedy algorithm (Chen and Lau, 1996; Papadimitriou and Steiglitz, 1998). Offutt et al. (1995) considered several different orderings of test cases instead of a fixed one as in greedy approach. Marré and Bertolino (2003) considered finding the minimal spanning set over *decision-to-decision* graph. Tallam and Gupta (2006) introduced delayed greedy approach. Jeffrey and Gupta (2005, 2007) used two testing requirements; branch coverage and *all-uses* coverage together which provided better fault detection capability. The basic idea is, if a test case is redundant in one but not in other, even then it is selected. Black et al. (2004) used bi-criteria approach and applied weighted sum and integer linear programming to find optimal subsets. Hsu and Orso (2009) considered multi-criteria test suite minimization using prioritized optimization and weighted sum approach. Yoo and Harman (2007) treated the problem of time aware prioritization. McMaster and Memon (2008) proposed minimization based on call stack coverage. Harder et al. (2003) used operational abstraction which is formal mathematical description of program behavior and checked if the removal of a test case changes the detected program invariant. Schroeder and Korel (2000) proposed an approach for black box testing minimization which identifies for each output variable, the set of inputs that can affect the output.

Out of all these techniques for test suite minimization; Greedy, GE and GRE heuristics have been used to find minimal cover of test cases, to cover all the requirements of an industrial software system, the SCAN tool.

3 APPROACH

It is proposed to implement Greedy, GE and GRE heuristics along with their *k*-coverage variants to find representative set of test cases to cover all the requirements.

3.1 Greedy Heuristics

The greedy approach selects the test case which satisfies the maximum number of uncovered requirements. The approach is described in Algorithm 1 and it takes the following inputs:

- *map* - mapping (*m*x*n*) between the test cases and the requirements
- *min* - minimal test suite (initially {})
- *cov* - requirements covered by the selected test cases in *min* (initially {})

The algorithm first checks if all the requirements have been covered or not. If yes, it returns the minimal test suite (*min*). Otherwise, it finds out the number of uncovered requirements covered by each test case which is not in *min*. If none of these test cases cover any uncovered requirements, then the coverage is not possible, the uncovered requirements are printed and *min* is returned which covers the requirements in *cov*. Otherwise, the test case which covers the maximum uncovered requirements is added to *min*. Then, all the uncovered requirements covered by this test case are added to *cov*. The algorithm again checks if all the requirements have been covered or not and the entire procedure is repeated.

Based on time and resources at hand, test team can also target to find 2-cover which covers all the requirements twice. Similarly, 3, 4, ... *k*-cover can also be found. The algorithm for *k*-coverage is similar to Algorithm 1. It also takes *k* as an input which denotes the required cover. Now, number of times a requirement has been covered needs to be tracked and it is added to *cov* when it is covered by *k* test cases in *min*.

3.2 GE Heuristics

GE heuristics first selects essential test cases which contain a requirement which is not satisfied by any another test case and then it selects test cases which satisfy the maximum number of uncovered requirements using greedy approach. The approach is described in Algorithm 2 and it takes the same inputs as taken by Algorithm 1. The algorithm scans each uncovered requirement and checks if it is satisfied by only one test case. Such a test case is considered as

Algorithm 1: Greedy approach.

```
   Input: map, min, cov
   Output: min
1  greedy (map, min, cov)
2  {
3      set flag = 0;
4      if !(all requirements ⊆ cov) then
5          set flag = 1;
6      end
7      while flag == 1 do
8          calculate number of uncovered
             requirements covered by each test case
             ∉ min;
9          if none of the test cases ∉ min cover any
             uncovered requirements then
10             print coverage is not possible;
11             print the uncovered requirements;
12             return min;
13         end
14         else
15             add test case covering maximum
                 uncovered requirements in min;
16             update cov;
17             set flag = 0;
18             if !(all requirements ⊆ cov) then
19                 set flag = 1;
20             end
21         end
22     end
23     return min;
24 }
```

Algorithm 2: GE heuristics.

```
   Input: map, min, cov
   Output: min
1  geheuristics (map, min, cov)
2  {
3      for (r = 1; r ≤ n; r++) do
4          if r ∉ cov and is covered by only one test
             case t_m then
5              add t_m in min;
6              update cov;
7          end
8      end
9      greedy (map, min, cov);
10 }
```

an essential test case and it is added to *min*. All uncovered requirements which are covered by this test case are added in *cov*. Once the scanning is complete, a call is made to Algorithm 1.

In k-coverage, if a requirement is covered by exactly k test cases then all those test cases are considered as essential test cases. For implementing k-cover using GE heuristics, Algorithm 3 is described which takes four inputs. First three inputs are similar to Algorithm 2 and fourth input is k, which is the desired cover. For each requirement which is not covered, the algorithm calculates the number of test cases which satisfy that requirement and store the test cases in set *choose*. If the number is less than k then k-coverage cannot be found. If it is greater than k, then there is no essential test case for that requirement and thus algorithm continues for the next requirement. If it is equal to k, then the test cases in *choose* which are not in *min* are added to *min* and *cov* is updated. A requirement is added to *cov* when it is covered by k test cases in *min*. Finally, the greedy algorithm is run to find the k-coverage.

Algorithm 3: k-coverage GE heuristics.

```
   Input: map, min, cov, k
   Output: min
1  geheuristics (map, min, cov, k)
2  {
3      for (r = 1; r ≤ n; r++) do
4          if r ∉ cov then
5              set count = 0;
6              set choose = {};
7              set count = number of test cases
                 covering r;
8              store all such test cases in choose;
9              if count < k then
10                 print k-coverage is not possible;
11             end
12             else if count > k then
13                 continue;
14             else
15                 for each test case t ∈ choose do
16                     if t ∉ min then
17                         print test case t is an
                             essential test case;
18                         add t to min;
19                         update cov;
20                     end
21                 end
22             end
23         end
24     end
25     greedy (map, min, cov, k);
26 }
```

3.3 GRE Heuristics

GRE heuristics initially removes the redundant test cases which satisfy a subset of the requirements satisfied by other test cases and then it selects the essential test cases. If some requirements are still uncovered, it selects the test cases greedily. Algorithm 4 describes the approach and it takes the same inputs as taken by Algorithm 1. The algorithm checks whether a test case t is a subset of another test case s for all the possible pairs of test cases. If t is found to be a subset of s then t is added in the *redundant* set, re-

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moved from the test suite and the *map* is updated. A call is made to Algorithm 2 when all the checking is completed.

In *k*-coverage, if a test case is found to be a subset of at least *k* test cases then the test case is considered redundant and removed from the test suite. For implementing *k*-cover using GRE heuristics, Algorithm 5 is described which takes four inputs similar to Algorithm 3. For each test case *t*, the algorithm calculates the number of test cases which are its superset. If the number is greater than or equal to *k*, *t* is removed from the test suite and *map* is updated accordingly. Finally, a call is made to Algorithm 3.

Algorithm 4: GRE heuristics.

Input: *map*, *min*, *cov*
Output: *min*

```
1  greheuristics (map, min, cov)
2  {
3      for (t = 1; t ≤ m; t++) do
4          for (s = 1; s ≤ m; s++) do
5              if ((map[t] ⊆ map[s]) && (s ≠
                t) && (s ∉ redundant)) then
6                  add t in redundant;
7                  update map;
8              end
9          end
10     end
11     geheuristics (map, min, cov);
12 }
```

Algorithm 5: *k*-coverage GRE heuristics.

Input: *map*, *min*, *cov*, *k*
Output: *min*

```
1  greheuristics (map, min, cov, k)
2  {
3      for (t = 1; t ≤ m; t++) do
4          set count = 0;
5          for (s = 1; s ≤ m; s++) do
6              if ((map[t] ⊆ map[s]) && (s ≠
                t) && (s ∉ redundant)) then
7                  count++;
8              end
9          end
10         if count ≥ k then
11             add t in redundant;
12             update map;
13         end
14     end
15     geheuristics (map, min, cov, k);
16 }
```

3.4 The Overall System

The SCAN tool takes an EDDL program and patterns of errors (requirements), R to be captured as an input. It generates a *.csv* file which contains all the the errors/warnings (subset of R) in the input program with detailed description, line number and severity level. During warning extraction, the subset, W of patterns of errors in R found in the input program is returned as shown in Figure 1.

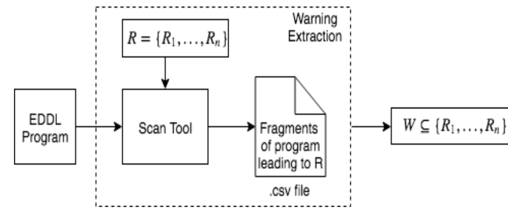

Figure 1: Warning extraction.

The overall process as shown in Figure 2 is followed. For the requirement coverage of SCAN tool, a set of EDDL programs/test cases, P are generated in each analysis. During warning extraction, for each test case P_i, a set of warnings, W_i is generated. Next, a mapping between test cases, P and requirements, R is obtained. The mapping is fed to Greedy, GE and GRE heuristics to obtain a minimal set of programs, $p \subseteq P$, which is sufficient to cover all requirements in R.

4 IMPLEMENTATION

The proposed algorithms have been implemented in Dev C++ 5.11 on Windows 10. In one of the versions of the SCAN tool, patterns of errors (requirements) listed in Table 1 are covered, based on the Software Requirements Specification (SRS) document provided by domain experts. A brief explanation of these requirements is given later in this section.

Initially, in analysis 1, test cases provided by testing team are considered and a mapping is constructed between the test cases and the requirements as shown in Table 2 where the rows T1, T2 ... T25 represents the test cases and the columns 1, 2 ... 21 represents the requirements R1, R2 ... R21. If a cell entry C_{ij} is 1 then test case T_i leads to error j and 0 if it does not. The mapping is fed to Greedy, GE and GRE heuristics and it is found that 8th, 14th, 18th and 19th requirements cannot be covered. These requirements are removed (reported as uncovered requirements to be taken care in the next version of the tool) in the refined mapping (having 17 requirements) which is fed again to the three heuristics. 2-cover is calculated using *k*-coverage Greedy, GE and GRE heuristics after removing requirement 15 (covered by only 1 test case). Similarly, 3-cover is calculated on further re-

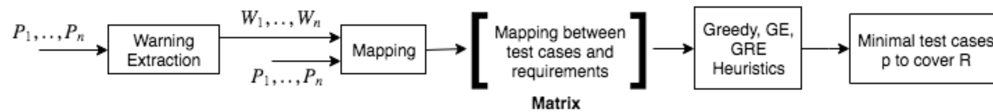

Figure 2: Overall process.

Table 1: Coarse grained requirements.

No.	Requirement
R1	Missing mandatory menus
R2	Unnecessary attributes usage in constructs
R3	Archaic built-ins usage
R4	Redefinition/duplicate definition
R5	Duplicate language definition
R6	Unsupported file format
R7	Enums defined but no value inside
R8	Incorrect variable names
R9	Use of assignment instead of equals
R10	Unused variables
R11	Uninitialized variables
R12	Multiple unit relationships not allowed
R13	String truncation
R14	Implicit cast
R15	Buffer overflow/underflow
R16	Arithmetic overflow/underflow
R17	Divide by zero
R18	Illegal arithmetic function calls
R19	Duplicate identifier
R20	Edit display usage
R21	Cyclic refresh relation

moving requirement 4 (covered by only 2 test cases). The results are discussed in Section 5 in Table 9.

In analysis 1, test cases 5 and 19 cover most of the requirements. To do a better analysis, each test case is designed keeping in consideration the requirement that is to be met. The obtained mapping given in Table 3 is then used in analysis 2. The results are discussed in Section 5 in Table 9. *k*-coverage heuristics return that 2-cover is not possible for requirements, 3, 4, 9, 15 and 21.

Although in analysis 2, coverage of requirements is found but still many bugs exist in the system as the requirements are considered at a very coarse grained level. In analysis 3, minimal cover is found for fine grained requirements. For each requirement, a brief description and sub-requirements considered are enumerated below.

- **R1:** Mandatory menus may be missing in the program. Sub-requirements are based on the mandatory menus specified by the user. SCAN tool gives flexibility to the user to customize the list of mandatory menus.
- **R2:** Some attributes may not be needed if a variable is not used in a menu. Sub-requirements are based on unrequired attributes.
- **R3:** Archaic or deprecated built-ins should not be used. Sub-requirements are based on the the archaic built-ins specified by the user.
- **R4:** Redefinitions inside the import section are not allowed at multiple levels and the variable being redefined must not be declared in the same file. Sub-requirements are based on these two conditions.
- **R5:** The language string should not be redefined. Sub-requirements are based on number of duplications and their location.
- **R6:** Usage of unsupported file format should lead to an error. Sub-requirements are based on user specified unsupported formats.
- **R7:** If Enums are defined without any initialization, a warning should be issued. Sub-requirements are based on enum types.
- **R8:** A warning should be issued if undeclared local and global variables are used for displaying their value inside a method. Sub-requirements are based on the used display function and printing format.
- **R9:** Usage of assignment operator inside a conditional expression should be flagged. Sub-requirements are based on level of nesting of the *if-else* construct.
- **R10:** Declaration of an item that has been defined, but not used within the scope of the application must be flagged. Sub-requirements are based on different types of items.
- **R11:** If a variable is defined but not initialized before use, a warning should be issued. Sub-requirements are based on different types of variables.
- **R12:** Multiple unit relationships between variables should be avoided, as it may lead to loops and race conditions. Sub-requirements are based on number of unit relationships.
- **R13:** Copying a larger string to a smaller string may result in string truncation which should be avoided. The assignment can be either be direct or through another string variable leading to two sub-requirements.
- **R14:** When assigning from one data type to another data type, an explicit type cast must be used to ensure it is done intentionally. To design sub-requirements, double data type is cast into different available data types.

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Table 2: Mapping of test cases and requirements in analysis 1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
T1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T2	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T3	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
T4	1	1	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
T5	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	1	1	0	0	1	1
T6	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T7	1	1	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1
T8	1	1	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1
T9	1	1	0	0	1	1	1	0	0	1	1	0	1	0	0	1	1	0	0	1	0
T10	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
T11	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
T12	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
T13	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
T14	1	1	0	0	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0
T15	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T16	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T17	0	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T18	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T19	1	1	1	1	1	1	1	0	1	1	0	1	0	0	0	1	1	0	0	1	1
T20	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0
T21	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0
T22	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
T23	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0
T24	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T25	1	1	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0

Table 3: Mapping of test cases and requirements in analysis 2.

	1	2	3	4	5	6	7	9	10	11	12	13	15	16	17	20	21
T1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
T2	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
T3	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
T4	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
T5	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
T6	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
T9	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
T10	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
T11	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
T12	1	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0
T13	1	1	0	0	1	1	1	0	1	1	0	1	0	1	1	1	0
T15	1	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0
T16	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0
T17	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0
T20	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
T21	1	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1

- **R15:** This may occur when an array tries to access an element outside its defined scope. Sub-requirements are designed based on whether the overflow or underflow is through an expression or it is done explicitly.
- **R16:** Each variable type has fixed amount of memory associated with it. The computations may lead to an assignment to a variable, making it too large or too small, for the variable type to handle. Sub-requirements are based on different variable types.
- **R17:** A run time error may occur if denominator of a division expression evaluates to zero. Sub-requirements are based on different patterns such as explicit division by 0, division by an expression evaluating to 0, conditional branch leading/not leading to divide by 0, or an assignment after divide by 0.
- **R18:** Arithmetic expressions and functions may be used with invalid arguments which should be avoided. For example, arguments of logarithm function may be negative. Sub-requirements are based on whether the argument is explicitly specified, or it is a variable or an expression.
- **R19:** The use of duplicate identifiers should be discouraged even when they are not in the same scope. Sub-requirements are based on identifiers for different items.
- **R20:** Usage of EDIT_DISPLAY should be flagged. One sub-requirement is kept for this.

Table 4: Fine grained requirements.

No.	Sub-Requirement	No.	Sub-Requirement	No.	Sub-Requirement
R1a	device root menu	R8c	put_message-format 3	R14g	unsigned short-double
R1b	diagnostics root menu	R8d	display-format 1	R14h	unsigned int-double
R1c	offline root menu	R8e	display-format 2	R14i	unsigned long-double
R1d	process variables root menu	R8f	display-format 3	R14j	unsigned long long-double
R1e	root menu	R8g	acknowledge-format 1	R14k	float-double
R1f	upload variables	R8h	acknowledge-format 2	R15a	explicit overflow
R1g	download variables	R8i	acknowledge-format 3	R15b	explicit underflow
R2a	default value	R9a	if	R15c	expression overflow
R2b	class	R9b	nesting level 2	R15d	expression underflow
R2c	help	R9c	nesting level 3	R16a	int/long
R2d	label	R10a	methods	R16b	short
R3a	assign_double	R10b	variables	R16c	long long
R3b	dassign	R10c	collections	R16d	char
R3c	fassign	R10d	arrays	R16e	unsigned char
R3d	assign_float	R10e	menus	R16f	unsigned short
R3e	iassign	R10f	grids	R16g	unsigned int/long
R3f	assign_int	R10g	charts	R16h	unsigned long long
R3g	vassign	R10h	images	R16i	float
R3h	assign_var	R11a	int	R16j	double
R3i	float_value	R11b	long	R17a	exp1/0
R3j	fvar_value	R11c	short	R17b	exp1/exp2 where exp2 valuates to 0
R3k	int_value	R11d	long long	R17c	conditional branch leading to divide by 0
R3l	ivar_value	R11e	char	R17d	conditional branch not leading to divide by 0
R3m	acknowledge	R11f	unsigned char	R17e	assignment after divide by 0
R4a	redefinition at multiple levels	R11g	unsigned short	R18a	log explicit
R4b	redefinition twice	R11h	unsigned int/long	R18b	log variable
R5a	single label	R11i	unsigned long long	R18c	log expression
R5b	single help	R11j	float	R19a	methods
R5c	double label	R11k	double	R19b	variables
R5d	double help	R12a	2 unit relations	R19c	collections
R5e	single label help	R12b	3 unit relations	R19d	arrays
R6a	.tiff	R13a	direct assignment	R19e	menus
R6b	.ppm	R13b	variable assignment	R19f	grids
R6c	.pgm	R14a	int-double	R19g	charts
R6d	.heif	R14b	long-double	R19h	images
R7a	bit enumerated	R14c	short-double	R20a	edit display usage
R7b	enumerated	R14d	long long-double	R21a	cycle of length 2
R8a	put_message-format 1	R14e	char-double	R21b	cycle of length 3
R8b	put_message-format 2	R14f	unsigned char-double	R21c	cycle of length 4

- **R21:** In a refresh relationship, cyclic dependency can happen which should be avoided, e.g. variable A is refreshed when variable B gets updated and variable B is refreshed when variable A gets updated. Sub-requirements are based on length of the cycle.

A complete list of sub-requirements is given in Table 4 where $R\alpha\beta$ represents requirement α and sub-requirement β. Mapping for analysis 3 in the form of adjacency list is given in Table 5. It is important to note that the mapping has been done manually and the analysis is only complete with respect to SRS and sub-requirements listed in Table 4. Test case $T\alpha\beta$ is designed to test requirement $R\alpha\beta$. In some cases, $T\alpha\beta$ does not meet $R\alpha\beta$. One of the reasons is that the pattern of error in consideration in that requirement is not handled by the current version of the tool. Also, in some cases, the user has not selected the pattern in the rule definition file which defines the patterns of errors to be detected by the tool. In certain test cases, the tool hangs, as the underlying parser could not parse the test case. The uncovered requirements are summarized here:

- assign_float requirement under archaic built-ins usage is not covered since the user has not selected the pattern in the rule definition file.
- double_label and double_help under duplicate language definition are not detected by the current version.
- All the sub-requirements under incorrect variable names are not handled by the current version.
- Grids under unused variables are not detected by the current version.
- Under uninitialized variables; short, char, unsigned char, unsigned short, unsigned int, long, long long, unsigned long, unsigned long long and double are not handled in the current version.
- String truncation for direct assignment is not captured in the current version.
- Tool hangs in case of explicit buffer underflow as negative numbers are not parsed in the index of

Table 5: Mapping of test cases and requirements in analysis 3.

Test Case	Requirement
T1a	R1a
T1b	R1b
T1c	R1c
T1d	R1d
T1e	R1e
T1f	R1f
T1g	R1g
T2a	R2a, R10b
T2b	R2b, R10b
T2c	R2c, R10b
T2d	R2d, R10b
T3a	R2a, R3a, R10a
T3b	R2a, R3b, R10a
T3c	R2a, R3c, R10a
T3d	R2a, R10a
T3e	R2a, R3e, R10a
T3f	R2a, R3f, R10a
T3g	R2a, R3g, R10a
T3h	R2a, R3h, R10a
T3i	R2a, R3i, R10a
T3j	R2a, R3j, R10a
T3k	R2a, R3k, R10a
T3l	R2a, R3l, R10a
T3m	R3m, R10a
T4a	R4a
T4b	R4b, R10b
T5a	R5a, R10g
T5b	R5b, R10g
T5c	R5a, R10g
T5d	R5b, R10g
T5e	R5a, R5b, R5e, R10g
T6a	R6a, R10h
T6b	R6b, R10h
T6c	R6c, R10h
T6d	R6d, R10h
T7a	R7a, R10b
T7b	R7b, R10b
T8a	R2a, R10a, R10b
T8b	R2a, R10a, R10b
T8c	R2a, R10a, R10b
T8d	R2a, R10a, R10b
T8e	R2a, R10a, R10b
T8f	R2a, R10a, R10b
T8g	R2a, R3m, R10a, R10b
T8h	R2a, R3m, R10a, R10b
T8i	R2a, R3m, R10a, R10b
T9a	R9a, R10a
T9b	R9b, R10a
T9c	R9c,R10a
T10a	R10a
T10b	R10b
T10c	R10c
T10d	R10d
T10e	R10e
T10f	
T10g	R10g
T10h	R10h
T11a	R10a, R11a
T11b	R10a
T11c	R10a
T11d	R10a
T11e	R10a
T11f	R10a
T11g	R10a
T11h	R10a
T11i	R10a
T11j	R10a, R11j
T11k	R10a
T12a	R12a
T12b	R12b
T13a	R10a
T13b	R10a, R13b
T14a	R10a, R14a
T14b	R10a, R14b
T14c	R10a, R14c
T14d	R10a, R14d
T14e	R10a, R14e
T14f	R10a, R14f
T14g	R10a, R14g
T14h	R10a, R14h
T14i	R10a, R14i
T14j	R10a, R14j
T14k	R10a, R14k
T15a	R10a, R15a
T15b	
T15c	
T15d	
T16a	R10a, R16a
T16b	R10a, R16b
T16c	
T16d	R10a
T16e	R10a
T16f	R10a
T16g	R10a
T16h	
T16i	R10a, R16i
T16j	
T17a	R10a, R16a, R17a
T17b	R10a, R16a, R17b
T17c	R10a, R16a, R17b, R17c
T17d	R10a, R16a, R17b, R17d
T17e	R10a
T18a	R10a, R18a
T18b	R10a, R18b
T18c	R10a, R18c
T19a	
T19b	
T19c	
T19d	
T19e	
T19f	
T19g	
T19h	
T20a	R20a
T21a	R21a
T21b	R21b
T21c	R21c

the array. Similar behaviour is observed for expression overflow and underflow as expression in the index of the array is not parsed.

- Arithmetic overflow is not covered for char, unsigned char, unsigned short, unsigned int and unsigned long. Tool hangs on double as C# cannot parse such big numbers as supported by EDDL. It also hangs on long long and unsigned long long variables. The range for unsigned long long and long long is 20 digits but Irony parser can support only 19 digits.
- In divide by zero, assignment after divide by zero is not covered.
- All the requirements under duplicate identifier are not met. The tool hangs as the identifiers are stored using a dictionary.

The cover cannot be found in Analysis 3 as many of the requirements are not met. Appropriate changes are incorporated in the next version of the tool to resolve all the reported errors. Analysis 4 is done on the new version of the tool and the mapping listed in Table 6 is obtained. In this analysis, the only requirements that can not be covered are arithmetic overflow for long long, unsigned long long and double. These are reported as the limitations of the tool. Arithmetic overflow of long long and unsigned long long can not be captured as the Irony parser used in the tool for parsing EDDL files can support only 19 digits. By taking any number whose value is more than 19 digits, the parser is not able to parse the file and the tool hangs. Arithmetic overflow of double can not be captured as C# used for coding the tool does not support the entire range of double supported by EDDL. The coverage is found for all the other requirements and the results are discussed in Section 5 in Table 10. It is not possible to find the 2-cover, as most of the requirements are met by only one test case.

5 RESULTS

In general it is not possible to grade the coverage provided by Greedy, GE and GRE heuristics (Yoo and

Table 6: Mapping of test cases and requirements in analysis 4.

Test Case	Requirement
T1a	R1a
T1b	R1b
T1c	R1c
T1d	R1d
T1e	R1e
T1f	R1f
T1g	R1g
T2a	R2a, R10b
T2b	R2b, R10b
T2c	R2c, R10b
T2d	R2d, R10b
T3a	R2a, R3a, R10a
T3b	R2a, R3b, R10a
T3c	R2a, R3c, R10a
T3d	R2a, R3d, R10a
T3e	R2a, R3e, R10a
T3f	R2a, R3f, R10a
T3g	R2a, R3g, R10a
T3h	R2a, R3h, R10a
T3i	R2a, R3i, R10a
T3j	R2a, R3j, R10a
T3k	R2a, R3k, R10a
T3l	R2a, R3l, R10a
T3m	R3m, R10a
T4a	R4a
T4b	R4b, R10b
T5a	R5a, R10g
T5b	R5b, R10g
T5c	R5a, R5c, R10g
T5d	R5b, R5d, R10g
T5e	R5a, R5b, R5e, R10g
T6a	R6a, R10h
T6b	R6b, R10h
T6c	R6c, R10h
T6d	R6d, R10h
T7a	R7a, R10b
T7b	R7b, R10b
T8a	R2a, R8a, R10a, R10b
T8b	R2a, R8b, R10a, R10b
T8c	R2a, R8c, R10a, R10b
T8d	R2a, R8d, R10a, R10b
T8e	R2a, R8e, R10a, R10b
T8f	R2a, R8f, R10a, R10b
T8g	R2a, R3m, R8g, R10a, R10b
T8h	R2a, R3m, R8h, R10a, R10b
T8i	R2a, R3m, R8i, R10a, R10b
T9a	R9a, R10a
T9b	R9b, R10a
T9c	R9c,R10a
T10a	R10a
T10b	R10b
T10c	R10c
T10d	R10d
T10e	R10e
T10f	R10f
T10g	R10g
T10h	R10h
T11a	R10a, R11a
T11b	R10a, R11b
T11c	R10a, R11c
T11d	R10a, R11d
T11e	R10a, R11e
T11f	R10a, R11f
T11g	R10a, R11g
T11h	R10a, R11h
T11i	R10a, R11i
T11j	R10a, R11j
T11k	R10a, R11k
T12a	R12a
T12b	R12b
T13a	R10a, R13a
T13b	R10a, R13b
T14a	R10a, R14a
T14b	R10a, R14b
T14c	R10a, R14c
T14d	R10a, R14d
T14e	R10a, R14e
T14f	R10a, R14f
T14g	R10a, R14g
T14h	R10a, R14h
T14i	R10a, R14i
T14j	R10a, R14j
T14k	R10a, R14k
T15a	R10a, R15a
T15b	R10a, R15b
T15c	R10a, R15c
T15d	R10a, R15d
T16a	R10a, R16a
T16b	R10a, R16b
T16c	
T16d	R10a, R16d
T16e	R10a, R16e
T16f	R10a, R16f
T16g	R10a, R16g
T16h	
T16i	R10a, R16i
T16j	
T17a	R10a, R16a, R17a
T17b	R10a, R16a, R17b
T17c	R10a, R16a, R17b, R17c
T17d	R10a, R16a, R17b, R17d
T17e	R10a, R16a, R17b, R17e
T18a	R10a, R18a
T18b	R10a, R18b
T18c	R10a, R18c
T19a	R10a, R19a
T19b	R10b, R19b
T19c	R10c, R19c
T19d	R10d, R19d
T19e	R10e, R19e
T19f	R10f, R19f
T19g	R10g, R19g
T19h	R10h, R19h
T20a	R20a
T21a	R21a
T21b	R21b
T21c	R21c

Harman, 2012). Given a set of requirements, a set of test cases, and a mapping between them, any of the three heuristics can give better results. For instance, if we compare GE and GRE, in mapping given in Table 7, adopted from Chen and Lau (1995), GE selects 4 test cases and GRE selects 5 test cases.

Table 7: Greedy and GE better than GRE.

	1	2	3	4	5	6	7	8	9	10	11
t1	1	1	1	1	1	0	0	0	0	0	0
t2	0	0	0	0	0	1	1	1	0	0	0
t3	0	0	0	0	0	0	0	0	1	1	0
t4	1	1	0	0	0	0	0	0	0	0	1
t5	0	0	0	1	1	1	1	0	0	0	0
t6	0	0	1	0	0	0	0	0	1	0	0
t7	0	0	0	0	0	0	0	0	0	0	1
t8	0	1	0	1	0	0	0	1	0	0	0
t9	0	0	0	0	1	0	0	0	0	1	0

But in mapping given in Table 8 GE selects 3 test cases and GRE selects 2 test cases. To compare Greedy and GRE, in mapping given in Table 7, Greedy selects 4 test cases and GRE selects 5 test cases. But in mapping given in Table 8, Greedy selects 3 test cases and GRE selects 2 test cases. To compare Greedy and GE, if we consider mapping given in Table 7 and remove t7 from it, in the obtained mapping, Greedy selects 4 test cases and GE selects 5 test cases. But if we consider mapping given in Table 8 and remove t5 from it, in the obtained mapping, Greedy selects 3 test cases and GE selects 2 test cases. Thus, any of these heuristics can give better output.

Table 8: GRE better than Greedy and GE.

	1	2	3	4
t1	1	0	0	1
t2	1	0	1	0
t3	0	0	1	1
t4	1	1	0	0
t5	0	1	0	0

Considering analysis 1, it can clearly be observed from Table 9 that for k=1, GE and GRE give better results than Greedy heuristics while for k=2 and k=3 all the approaches give similar results. An obvious observation is that with increasing k, more test cases are needed to cover the requirements, which also points towards the convergence of these algorithms. For analyses 2 and 4, as evident from Table 9 and Table

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Table 9: Results of analysis 1 and analysis 2.

Cover	Analysis 1 (k=1)		Analysis 1 (k=2)		Analysis 1 (k=3)		Analysis 2 (k=1)	
Uncovered Requirements	8, 14, 18, 19		8, 14, 15, 18, 19		8, 4, 14, 15, 18, 19		8, 14, 18, 19	
Approach	Test Cases	No.	Test Cases	No.	Test Cases	No.	Test Cases	No.
Greedy	5, 9, 15, 21	4	5, 9, 14, 15, 19	5	5, 7, 9, 14, 19, 22, 23, 24	8	3, 4, 9, 13, 15, 21	6
GE	9, 19, 21	3	5, 9, 14, 15, 19	5	5, 7, 9, 14, 19, 22, 23, 24	8	3, 4, 9, 13, 15, 21	6
GRE	9, 19, 21	3	5, 9, 14, 15, 19	5	5, 8, 9, 14, 19, 22, 23, 24	8	3, 4, 9, 13, 15, 21	6

Table 10: Results of analysis 4.

Cover	k=1	
Uncovered Requirements	R16c, R16h, R16j	
Approach	Test Cases	No.
Greedy	T1a, T1b, T1c, T1d, T1e, T1f, T1g, T2b, T2c, T2d, T3a, T3b, T3c, T3d, T3e, T3f, T3g, T3h, T3i, T3j, T3k, T3l, T4a, T4b, T5c, T5d, T5e, T6a, T6b, T6c, T6d, T7a, T7b, T8a, T8b, T8c, T8d, T8e, T8f, T8g, T8h, T8i, T9a, T9b, T9c, T11a, T11b, T11c, T11d, T11e, T11f, T11g, T11h, T11i, T11j, T11k, T12a, T12b, T13a, T13b, T14a, T14b, T14c, T14d, T14e, T14f, T14g, T14h, T14i, T14j, T14k, T15a, T15b, T15c, T15d, T16b, T16d, T16e, T16f, T16g, T16i, T17a, T17c, T17d, T17e, T18a, T18b, T18c, T19a, T19b, T19c, T19d, T19e, T19f, T19g, T19h, T20a, T21a, T21b, T21c	100
GE	Same as Greedy	100
GRE	Same as Greedy	100

10 respectively, all approaches output the same number of test cases to cover the requirements. The early convergence for k=1 can be attributed to sparsity of the input matrices and small value of $r_{overlap}$ (average number of test cases which meet a requirement) and a large number of essential test cases thus leaving very less alternatives to select.

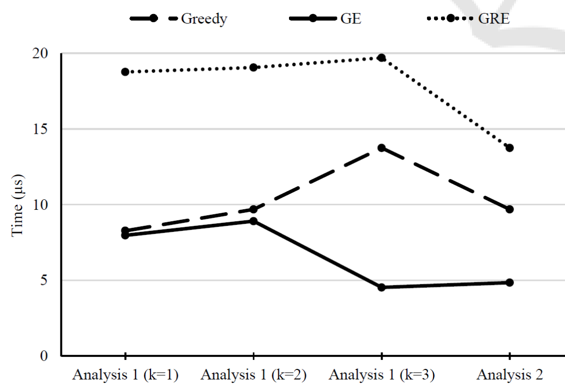

Figure 3: Run time performance comparison.

Figure 3 presents the run time performance of Greedy, GE and GRE heuristics in analyses 1 and 2. In analysis 4, Greedy takes 3862.88 μs, GE takes 177.82 μs and GRE takes 2953.98 μs. It can clearly be observed, in all these analyses, GE performs the best (GE takes considerably less time than Greedy in analysis 1 (k=3), analysis 2 and analysis 4 as there are many essential test cases), followed by Greedy, and then GRE performs the worst (GRE wastes a lot of time in pre-processing to remove redundant test cases). In analysis 4, GRE performs better than Greedy because its overhead of redundant calculation is balanced by its essential pass. In software systems, if $r_{overlap}$ is small and many essential test cases exist, all heuristics will give similar output but run time of GE will be the least and thus should be preferred.

If more requirements are added, the existing mapping can be reused. For this, the mapping of existing test cases with respect to the new requirements needs to be filled. Extra test cases to cover them may also be designed and mapped. Similarly, if a subset of requirements needs to be considered, the existing map can be reused. The additional requirements and the corresponding map can simply be removed.

The major limitation of the heuristics used is that they do not give any weightage to the time required to run a test case. In future, techniques may be considered which also focus on the run time of a test case.

6 CONCLUSION

In this paper, Greedy, GE and GRE heuristics have been successfully used to cover the specified requirements (in SRS) of the SUT, the SCAN tool. The minimal cover obtained helps in reducing testing time and effort while doing regression testing. Existing mapping of test cases and requirements can be reused while adding or removing requirements. k-cover can be applied if better assurance about coverage is required at the cost of more testing effort and time. Learning algorithms can be designed to find an optimal value of k. In general, it would be tough to rank the efficiency of Greedy, GE and GRE heuristics as they are based on heuristics and none of these is a precise algorithm. A comparison of output and run time performance of these heuristics for a given set of test cases and requirements has been presented for each analysis done on the SCAN tool. It has been observed that if $r_{overlap}$ is small and there are many essential test cases, all the heuristics give similar output but GE has the best run time performance and thus, it is advisable to use GE heuristics in such a scenario. Future work could include an empirical evaluation to find out the range of $r_{overlap}$ and percentage of essential

test cases. To ensure, all requirements are addressed properly and covered efficiently, requirements should be fine grained and then mapped, which in turn also helps in finding bugs in each version of the SUT.

Efficiency of these heuristics can be tested and validated on the upcoming versions of the SCAN tool. Further, these heuristics can be applied on other evolving software systems, leading to better confidence about behavior and correctness of these systems. The heuristics can be evaluated for other values of $r_{overlap}$. Other heuristics such as HGS and multi-objective optimization can also be evaluated and compared. The test cases designed here might not be covering entire code of the SUT and thus, code coverage can be applied using similar techniques. Automated generation of test cases based on code coverage is a prominent direction to work upon. Further, techniques which also focus on the time taken to execute a test case may be considered. Instead of obtaining the mapping manually, automated generation of mapping for a given set of requirements and test cases can be explored. Dynamic code analysis tools for EDDL can also be designed in future.

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