Code Coverage of Adaptive Random Testing

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Abstract—Random testing is a basic software testing technique that can be used to assess the software reliability as well as to detect software failures. Adaptive random testing has been proposed to enhance the failure-detection capability of random testing. Previous studies have shown that adaptive random testing can use fewer test cases than random testing to detect the first software failure. In this paper, we evaluate and compare the performance of adaptive random testing and random testing from another perspective, that of code coverage. As shown in various investigations, a higher code coverage not only brings a higher failure-detection capability, but also improves the effectiveness of software reliability estimation. We conduct a series of experiments based on two categories of code coverage criteria: structure-based coverage, and fault-based coverage. Adaptive random testing can achieve higher code coverage than random testing with the same number of test cases. Our experimental results imply that, in addition to having a better failure-detection capability than random testing, adaptive random testing also delivers a higher effectiveness in assessing software reliability, and a higher confidence in the reliability of the software under test even when no failure is detected.

Index Terms—Adaptive random testing, code coverage, failure-based testing, random testing.

ACRONYMS

RT	Random Testing
ART	Adaptive Random Testing
FSCS-ART	Fixed-Sized-Candidate-Set Adaptive Random Testing
CPM	Category Partition Method

NOTATION

$\backslash$	The set difference operator
$|\cdot|$	The size of a set
$A_{x_{i_j}}$	The jth category for a program input x_i
$O_{x_i}^{x_{i_j}}$	The choice of category $A_{x_{i_j}}$ for x_i

$\mathbf{A}(x_i)$	The list of categories associated with x_i, that is, $\{A_{x_{i_1}}, A_{x_{i_2}}, \cdots, A_{x_{i_q}}\}$
$\mathbf{O}(x_i)$	The list of choices associated with x_i, that is, $\{O_{x_i}^{x_{i_1}}, O_{x_i}^{x_{i_2}}, \cdots, O_{x_i}^{x_{i_q}}\}$
$\widehat{\mathbf{O}}(x_1, x_2)$	The set of distinct choices for inputs x_1 and x_2, that is, $(\mathbf{O}(x_1) \cup \mathbf{O}(x_2)) \backslash (\mathbf{O}(x_1) \cap \mathbf{O}(x_2))$
$\widehat{\mathbf{A}}(x_1, x_2)$	The set of distinct categories for inputs x_1 and x_2, that is, $\{A_h | A_l, \text{if } \exists O_t^l \in \widehat{\mathbf{O}}(x_1, x_2)\}$
N_s	The total number of certain elements in the program under test (such as statements, decisions, c-uses, p-uses, etc.)
N_i	The number of infeasible program elements
N_c	The number of program elements covered by a test set
M_n	The total number of mutants generated
M_a	The number of mutants that are syntactically incorrect and thus cannot be compiled
M_t	The number of mutants that can be compiled successfully, that is, $M_n - M_a$
M_q	The number of equivalent mutants
M_k	The number of killed mutants

I. INTRODUCTION

SOFTWARE testing, a major approach to software quality assurance, is widely acknowledged as a vital activity throughout the software development process. Many software testing methods are accomplished by defining test objectives, selecting some inputs of the software under test as *test cases*, executing the software with these test cases, and verifying testing results. Because software normally has an extremely large *input domain* (that is, the set of all possible inputs for the software under test), testers are always required to select a certain portion of the input domain as test cases such that software failures can be effectively detected within the limited testing resources. A large number of software testing methods have been proposed to guide the test case selection.

Random testing (RT) is a fundamental testing method which simply selects test cases in a random manner from the whole input domain [33]. RT has been popularly applied to assess software reliability. However, its effectiveness at detecting software failures is debatable. Myers [33] criticized that RT may be the "least effective" testing method for using little or no information about the software under test. Menzies and Cukic [29], based on a series of simulations, claimed that RT could "adequately

probe the software" under many situations. Duran and Ntafos [18] conducted some simulations to compare RT with a particular class of testing methods, partition testing, which divides the whole input domain into disjoint partitions, and then selects test cases from these partitions. They found that RT may be more cost-effective than partition testing.

In spite of controversies about its effectiveness, RT has been successfully used in different areas for detecting various failures. For example, Miller *et al.* [31], [32] have used RT to test UNIX utility programs, and reported that a large number of UNIX programs have been crashed or hanged by test cases generated using RT. Forrester and Miller [19] applied the RT technique to test Windows NT applications, and it was observed that 21% of tested applications were crashed, and an additional 24% of applications were hanged. RT has also been used in the testing of graphical user interfaces [15], Java Just-In-Time compilers [47], and embedded software systems [36]. Moreover, RT has been adopted in many industrial automatic testing tools, such as those developed by IBM [3], Microsoft [39], and Bell Labs [20].

Inputs that cause the program under test to exhibit failure behaviors are named as *failure-causing inputs*. Researchers from various areas [2], [4], [42], [43] have made a common observation that failure-causing inputs often cluster into contiguous *failure regions*. White and Cohen [43], for example, found that contiguous failure regions often result from a common type of software fault, namely domain error, which refers to an error located in a decision of a program. Ammann and Knight [2] studied some missile launch decision programs, and observed that "particular failure regions are locally continuous." Bishop [4] observed "blob defects," where all detected failure-causing inputs "occupied contiguous regions" in some nuclear reactor trip programs, and theoretically justified the existence of "blob defects." Van der Meulen *et al.* [42] collected a large number of faulty programs written in different languages by various programmers, and observed that most failure regions are contiguous.

Given that failure regions are frequently contiguous, it should also be common for non-failure regions to be contiguous. Under such situations, adjacent test cases often have similar behaviors in failure detection. If a test case t does not reveal any failure, a test case that is away from t is more likely to detect a failure than t's "neighbors" [12]. Based on such an intuition, Chen *et al.* [13] proposed a novel method, namely *adaptive random testing* (ART), to enhance the failure-detection capability of RT. In ART, test cases are not only randomly generated, but also evenly spread over the whole input domain. Previous studies have shown that ART is more effective than RT, not only because ART generally uses fewer test cases to detect the first failure than RT [11], but also because the failure-detection capability of ART is more reliable than that of RT [26]. As a consequence of a better failure-detection capability, ART can save testing resources, and the saving will become more significant when test case execution or test output verification is expensive. ART improves the performance of RT while keeping the randomness in the test case selection process.

The even spread of test cases, the basic notion of ART, is essentially a form of test case diversity [10] across the input domain of the software under test. The diversity of test cases is effectively the key concept for many testing techniques. For example, some code coverage criteria [48] have been used to guide the selection of diverse test cases such that certain program structures are covered[1], or certain types of faults are detected. Previous studies have shown that the coverage techniques not only enhance the failure-detection capability [22], [44], [45], [46], but also improve the effectiveness in assessing the software reliability [7]. Besides being used in the selection of test cases, these coverage criteria can also be applied to measure the adequacy of a *test set* (that is, a set of test cases)[48].

In this paper, we attempt to answer the following research question: apart from a better failure-detection capability than RT, does the test case diversity brought by ART across the input domain also result in higher code coverage? We conduct experimental studies to evaluate and compare the code coverage achieved by ART and RT. Our experimental results show that, given the same number of test cases, ART normally achieves higher code coverage than RT. Such an observation confirms that ART is a more effective testing method than RT, not only because it enhances the failure-detection capability, but also because it delivers a higher confidence on the software reliability.

The paper is organized as follows. In Section II, we introduce some background information about ART and code coverage criteria. In Sections III and IV, we report our experiments and the experimental results. In Section V, we discuss the threats to validity of our study. In Section VI, we conclude the paper.

II. PRELIMINARIES

A. ART Algorithm

Generally speaking, test cases selected by ART have two essential attributes: (*i*) randomness, and (*ii*) even spread. Most ART algorithms use two s-independent processes to ensure these attributes. One process is to randomly generate program inputs as *test case candidates*, or briefly *candidates*. The other process in ART is to apply certain criteria to select test cases from candidates such that the executed test cases are evenly spread over the input domain. One typical ART algorithm is called *fixed-size-candidate-set ART* (FSCS-ART) [13]. It maintains two sets of test cases. One set is the *executed set* $E = \{e_1, e_2, \cdots, e_n\}$, where $e_1, e_2, \cdots, e_n$ are all executed test cases; the other set is the *candidate set*, which contains k randomly generated inputs, denoted by $C = \{c_1, c_2, \cdots, c_k\}$, where k is fixed throughout the testing process. A candidate will be selected as the next test case if it has the longest distance to its nearest neighbor in E. Fig. 1 gives the detailed algorithm of FSCS-ART.

In Fig. 1, the termination condition can be "when the testing resources are exhausted," "when a certain number of test cases have been executed," "when the first failure is detected," etc. In most previous studies of ART, it was often assumed that the program under test only has numeric inputs, and the "distance" in Statement 8 of Fig. 1 often referred to the Euclidean distance between two points.

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[1] In this paper, "a program structure is covered" and "a program structure is executed" are used interchangeably

1. Input an integer k, where $k > 1$.
2. Set $n = 0$, and $E = \{\}$.
3. Randomly generate a test case t from the input domain.
4. **while** (termination condition does not satisfy)
5.   Add t into E, and increment n by 1.
6.   Randomly generate k candidates $c_1, c_2, \cdots, c_k$ from the input domain, and construct C with these candidates.
7.   **for** each candidate c_j, where $j = 1, 2, \cdots, k$.
8.   Calculate the distance d_j to its nearest neighbor in E.
9.   **end_for**
10.   Find $c_b \in C$ such that $\forall j = 1, 2, \cdots, k, d_b \geq d_j$.
11.   Set $t = c_b$.
12. **end_while**
13. Exit.

Fig. 1.   Algorithm of FSCS-ART.

TABLE I
SUBJECT PROGRAMS AND THEIR BASIC INFORMATION

Program	Functionality	Lines of code
Cal	Print a calendar for a specified year or month	163
Checkeq	Report missing or unbalanced delimiters and .EQ/.EN pairs	90
Col	Filter reverse paper motions for nroff output for display on a terminal	274
Comm	Select or reject lines common to two sorted files	144
Crypt	Encrypt and decrypt a file using a user supplied password	121
Look	Find words in the system dictionary or lines in a sorted list	135
Sort	Sort and merge files	842
Spline	Interpolate smooth curve based on given data	289
Tr	Translate characters	127
Uniq	Report or remove adjacent duplicate lines	125

TABLE II
NUMBER OF PROGRAM ELEMENTS FOR EACH SUBJECT PROGRAM

Program	blocks		decisions		c-uses		p-uses	
	N_s	N_i	N_s	N_i	N_s	N_i	N_s	N_i
Cal	94	0	51	0	112	10	97	15
Checkeq	73	0	70	7	76	14	77	26
Col	153	17	108	10	209	20	202	55
Comm	97	10	69	24	67	7	69	29
Crypt	70	8	42	7	74	6	61	16
Look	84	3	52	2	57	1	67	7
Sort	503	58	384	65	941	212	852	241
Spline	188	2	123	8	258	39	189	35
Tr	100	5	82	12	118	25	156	63
Uniq	79	3	58	3	62	4	66	10

The F-measure refers to the expected number of test cases required to detect the first software failure. Previous studies [10], [11], [13], [26] often used F-measure to examine and compare the failure-detection capabilities of ART and RT, and showed that ART normally has a smaller F-measure than RT. Liu and Zhu [26] also found that the F-measure of ART has smaller variation than that of RT, that is, ART has a more reliable failure-detection capability than RT.

Previous studies [12] on FSCS-ART have shown that, although the F-measure of FSCS-ART becomes smaller with the increase of k, any $k > 10$ will only marginally reduce the F-measure. $k = 10$ is a fair setting for balancing the trade-off between the failure-detection capability and the computation overhead of FSCS-ART. In this paper, we use FSCS-ART with $k = 10$ to study ART.

The basic intuition of ART is to evenly spread random test cases. Besides FSCS-ART, various ART algorithms have been proposed to achieve the goal of even spread, such as ART by dynamic partitioning [8], lattice-based ART [28], restricted random testing [6], etc. These ART algorithms have different ways of evenly spreading test cases, different failure-detection effectiveness, and different computation overheads. FSCS-ART requires $O(n^2)$ time to select n test cases. When the number of test cases is very large, some techniques, such as *forgetting* [5], can be used to reduce the runtime of FSCS-ART. By forgetting some executed test cases, the selection of a new test case may refer to a fixed number of the most recently executed test cases instead of all previously executed test cases. As a result, the test case selection time for FSCS-ART with forgetting can then be independent of n. Previous studies [5] also showed that such a forgetting technique does not significantly reduce the failure-detection effectiveness. In the experiment of this study, the number of test cases is no more than 1,000 (as shown in Section III), so we do not use the forgetting technique.

B. Application of ART Into Programs With Non-Numeric Inputs

Most previous studies on ART have assumed that the program under test only has numeric inputs. In these studies, the Euclidean distance is the metric for measuring the distance between inputs, and is used by ART to evenly spread test cases. However, there exist a great number of non-numeric programs (that is, programs with non-numeric inputs) in real life, and it is not so straightforward to measure the distance between two non-numeric inputs. Recently, a new metric, namely *category-partition-based metric*, has been proposed for non-numeric inputs [23], [30]. Some preliminary empirical studies have been conducted on this new metric [23], and the experimental results showed that ART usually has a better failure-detection capability than RT for programs with non-numeric inputs.

The basic intuition of such a metric is explained as follows. Intuitively speaking, if two program inputs trigger the same functionalities, they are likely to cause the program under test to have similar test outcomes (failure or pass). To effectively detect failures, successive test cases should differ from each other as much as possible with respect to the functionalities that they trigger. Instead of the Euclidean distance, the new metric attempts to measure the distance between two inputs in terms of the functionalities triggered by them. Category partition method (CPM) [34] was adopted to facilitate the measurement of the distance between two inputs. Traditionally, CPM is used to generate test cases. In CPM, testers first identify a set of categories and associated choices based on functionalities given in software specifications. Then they identify constraints among choices, generate test frames, and finally create one test case for each test frame.

Instead of using CPM to generate test cases, categories and choices are used to construct an *input classification scheme*. For example, an input x_i is associated with a list of categories $\mathbf{A}(x_i)$, and a list of choices $\mathbf{O}(x_i)$.
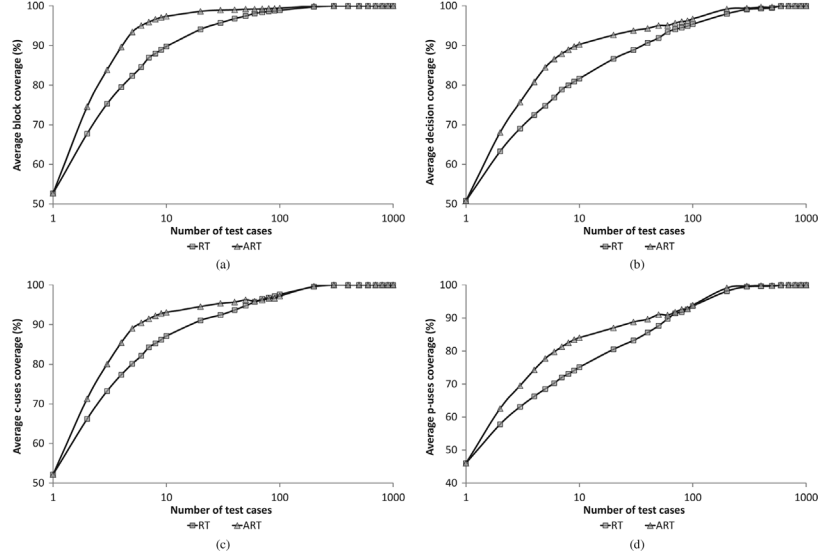
Fig. 2. Coverage percentages of ART and RT on the program `Cal`: (a) block coverage on `Cal`; (b) decision coverage on `Cal`; (c) C-uses coverage on `Cal`; (d) P-uses coverage on `Cal`.

TABLE III
MUTANT STATISTICS FOR SUBJECT PROGRAMS

Program	M_n	M_a	M_t	M_q
Cal	304	1	303	26
Checkeq	235	1	234	65
Col	454	0	454	427
Comm	247	4	243	47
Crypt	248	2	246	206
Look	162	7	155	39
Sort	1396	8	1388	1315
Spline	497	1	496	423
Tr	243	0	243	182
Uniq	196	4	192	25

Because these categories and choices are defined based on software functionalities, they can reflect the relationship between program inputs and their associated functionalities. Based on such a scheme, the distance between two inputs x_1 and x_2 can be calculated as follows. First, we construct the set of distinct choices $\widehat{\mathbf{O}}(x_1, x_2)$ for x_1 and x_2. Secondly, we construct the set of distinct categories $\widehat{\mathbf{A}}(x_1, x_2)$ for x_1 and x_2. Finally, we can calculate the distance between x_1 and x_2 as $|\widehat{\mathbf{A}}(x_1, x_2)|$.

C. Code Coverage Criteria

There are various code coverage criteria in the literature [48]. For example, *structure-based criteria* require the selected test cases to thoroughly execute certain elements in the structure of the software under test, while *fault-based coverage criteria* require the selected test cases to thoroughly detect various faults injected in the program.

Control-flow criteria and *data-flow* criteria are two typical structure-based coverage criteria. Control-flow coverage criteria [21] consider some control constructs of the program under test. For example, in statement testing strategy, test cases

are selected such that all feasible statements[2] in the program are executed at least once. Condition coverage is another example of control-flow testing strategy, which subsumes statement testing. In condition coverage testing, test cases are required to exercise both the true and false outcomes of each feasible condition in all feasible decisions. According to data-flow coverage criteria [24], test cases should thoroughly exercise certain patterns of data manipulation within the program under test. Patterns of data manipulation include the definition of a datum (abbreviated as `def`), where a value is allocated to the datum, and usage of a datum (abbreviated as `use`), where the datum's value is used by an operation. In addition, `use` can be further classified into $c - use$, where a datum is used in a computational expression or as an output; and $p - use$, where a datum appears in a predicate within the program. Many data-flow testing strategies have been proposed based on the above concepts, such as all-defs, all-p-uses, all-c-uses, and all-def-use-pairs coverage. Readers may be interested to find details of control-flow and data-flow coverage criteria from software testing literature [1], [27], [33], [35]. The percentage of control-flow or data-flow coverage (referred to as coverage percentage in the rest of this paper) that a test set can achieve is calculated as

$$\text{Coverage percentage} = \frac{N_c}{N_s - N_i} \times 100\%, \qquad (1)$$

Mutation analysis [17] is a popular approach for fault-based coverage. In code-based mutation analysis, mutation operators are applied to inject a set of predefined faults into a program. As a result, a number of variants, namely *mutants*, are generated based on the program under test. If a test case detects different behaviors between a mutant and the program, this test case is said to "kill" the mutant, and thus detect the fault seeded in the mutant. The performance of the constructed test set is measured

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[2]For a program element (such as statement, condition, etc.) to be feasible, the conditions along the path containing the element should not be contradictory to one another; otherwise, it is called an infeasible element.
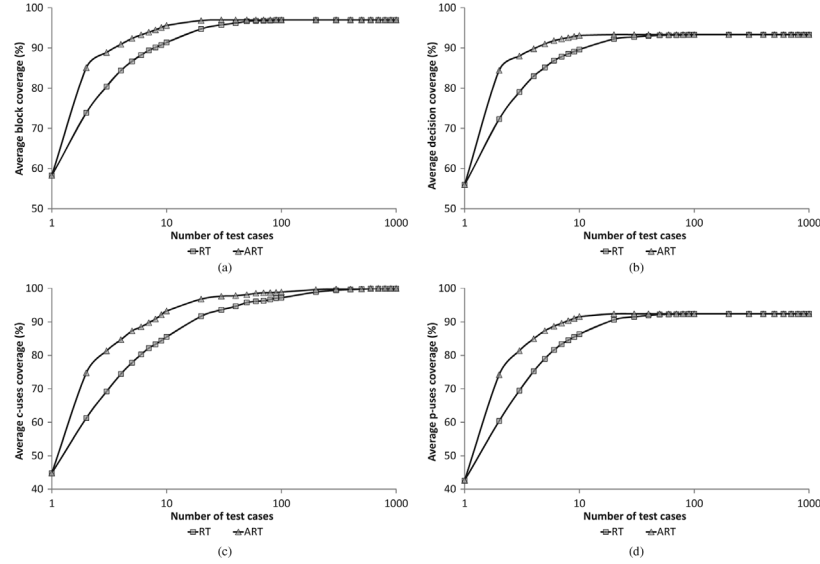
Fig. 3. Coverage percentages of ART and RT on the program `Checkeq`: (a) block coverage on `Checkeq`; (b) decision coverage on `Checkeq`; (c) C-uses coverage on `Checkeq`; (d) P-uses coverage on `Checkeq`.
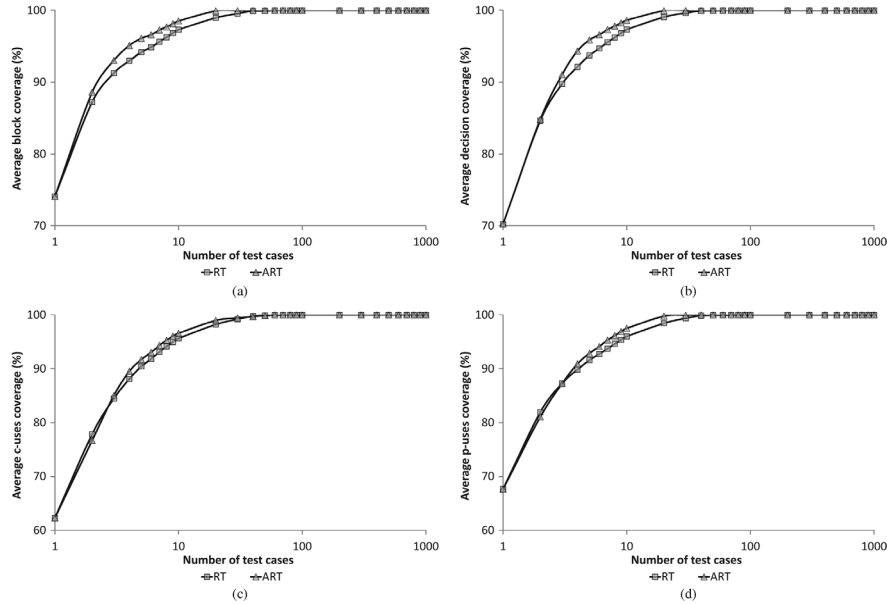

Fig. 4. Coverage percentages of ART and RT on the program `Col`: (a) block coverage on `Col`; (b) decision coverage on `Col`; (c) C-uses coverage on `Col`; (d) P-uses coverage on `Col`.

based on its ability to kill mutants. *Mutation score*, which is used to measure how thoroughly a test set can kill the mutants, is defined as

$$\text{Mutation score} = \frac{M_k}{M_t - M_q} \times 100\%, \qquad (2)$$

Many previous studies have shown the advantages of code coverage criteria from various perspectives. Hutchines *et al.* [22], for example, have used some coverage testing techniques to detect failures in "the Siemens suite." It was observed that the higher coverage a test set could achieve, the more failures would be revealed. Wong *et al.* [44] pointed out that the coverage achieved by a test set is strongly correlated to the failure-detection capability, while the size reduction of a test set has almost

no impact on the failure-detection capability as long as the coverage remains unchanged [45], [46]. Rothermel *et al.* [37] have used some coverage criteria as test case prioritization schemes. It was found that code coverage criteria can significantly enhance the failure-detection capability of the test case prioritization technique. Chen *et al.* [7] also observed that the coverage technique can even be applied to improve the effectiveness of software reliability estimation.

Code coverage criteria are very useful in the measurement of the quality of a test set [48]. If a test set achieves 100% coverage on the program under test in terms of a certain coverage criterion $\mathcal{C}$, this set is regarded as adequate with respect to $\mathcal{C}$. Given two testing strategies, each of which selects a test set of the same size, one strategy is considered better than the other from the
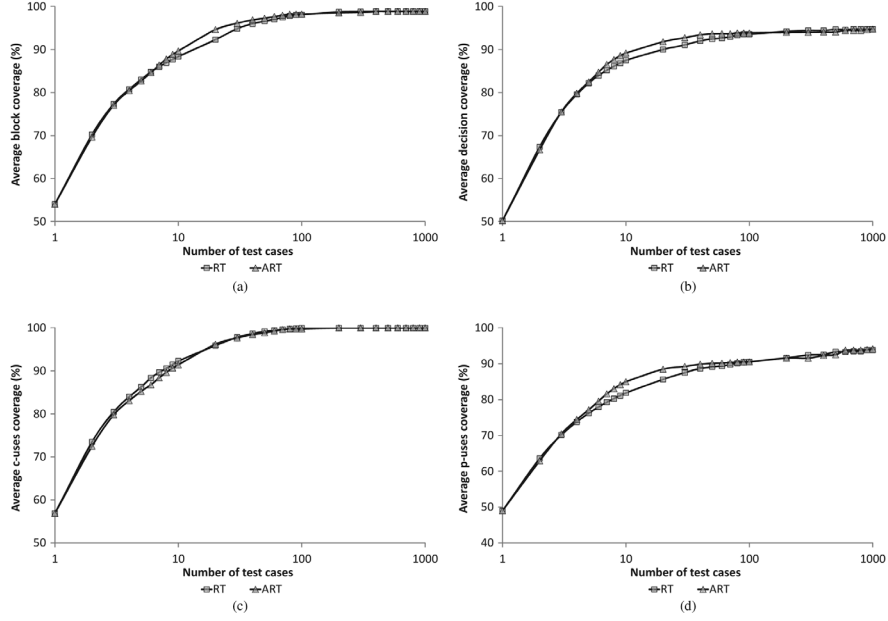
Fig. 5.   Coverage percentages of ART and RT on the program `Comm`: (a) block coverage on `Comm`; (b) decision coverage on `Comm`; (c) C-uses coverage on `Comm`; (d) P-uses coverage on `Comm`.
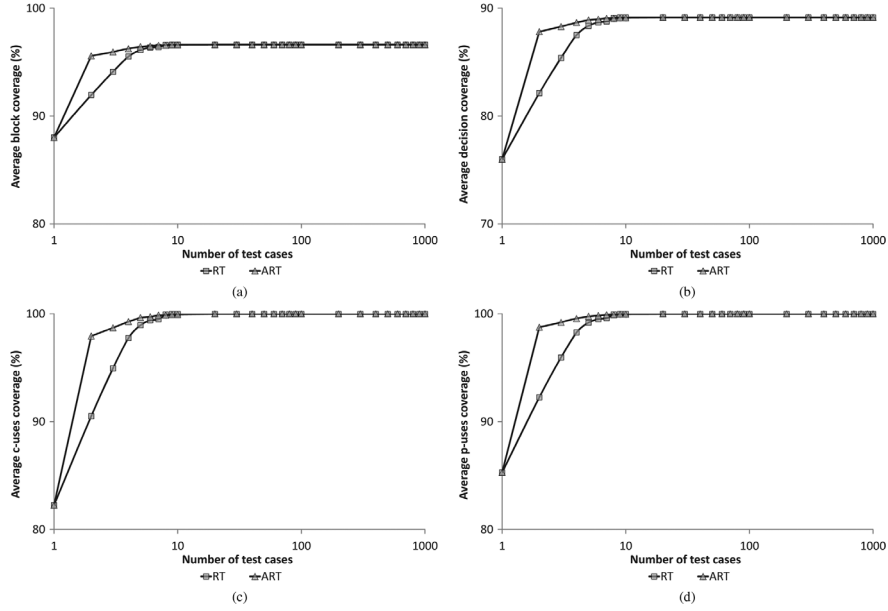

Fig. 6.   Coverage percentages of ART and RT on the program `Crypt`: (a) block coverage on `Crypt`; (b) decision coverage on `Crypt`; (c) C-uses coverage on `Crypt`; (d) P-uses coverage on `Crypt`.

perspective of C if its selected test set can achieve higher coverage.

III. EXPERIMENTAL SETTINGS

In our previous study [9], we investigated the performance of ART for programs with numeric inputs. Five programs were used to measure the structure-based coverage of ART. Each of these programs only accepts a fixed number of numeric inputs. However, in reality, there exist a large amount of programs that accept non-numeric inputs. In this study, we further investigate the performance of ART beyond programs with solely numeric inputs. We selected ten UNIX utility programs, namely `Cal`,

`Checkeq`, `Col`, `Comm`, `Crypt`, `Look`, `Sort`, `Spline`, `Tr`, and `Uniq` [45], as summarized in Table I. These subject programs have various types of inputs, such as strings, data files, etc.

In this study, we use the χ`Suds` tool developed by Telcordia Technologies [40] to analyze the structure-based coverage of a test set. χ`Suds` can evaluate both the control-flow and data-flow coverage, and output the coverage percentage that a test set can achieve. For control-flow coverage, χ`Suds` evaluates "block coverage" and "decision coverage". A block refers to a sequence of statements whose execution will not be interrupted by any decision. Therefore, the block coverage in χ`Suds` is effectively equivalent to statement coverage. The "decision
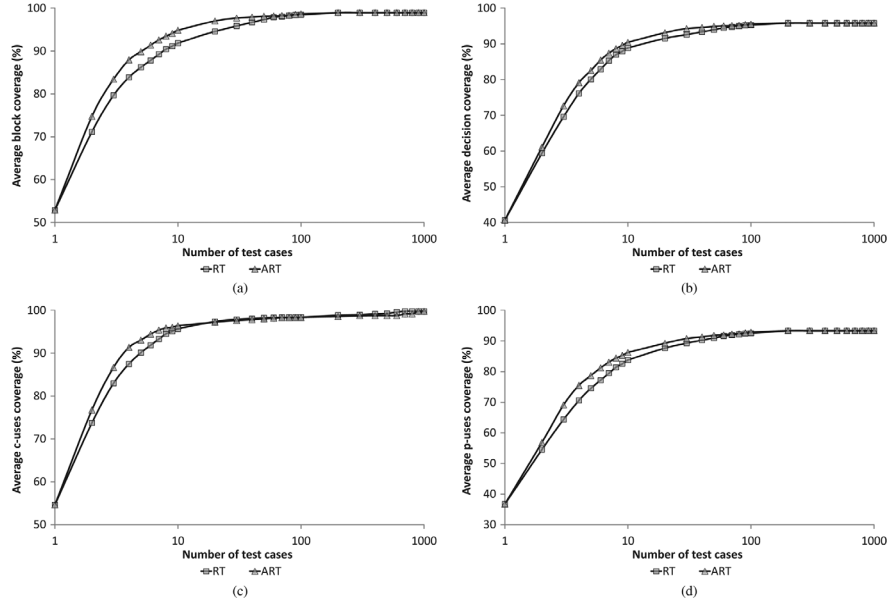
Fig. 7.   Coverage percentages of ART and RT on the program `Look`: (a) block coverage on `Look`; (b) decision coverage on `Look`; (c) C-uses coverage on `Look`; (d) P-uses coverage on `Look`.
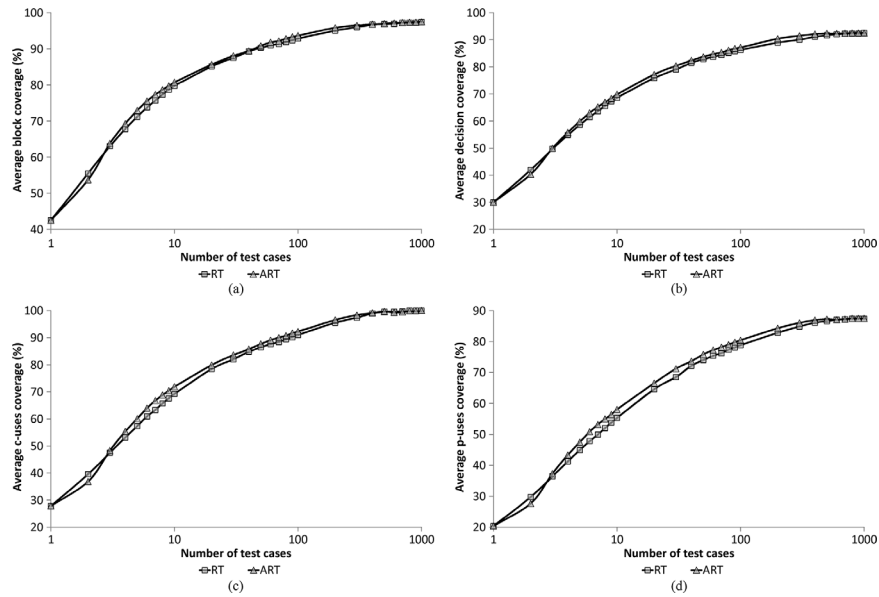

Fig. 8.   Coverage percentages of ART and RT on the program `Sort`: (a) block coverage on `Sort`; (b) decision coverage on `Sort`; (c) C-uses coverage on `Sort`; (d) P-uses coverage on `Sort`.

coverage" in χ`Suds` requires test cases to exercise both the true and false outcomes of all conditions in each decision of the program under test; that is, the "decision coverage" in χ`Suds` is effectively equivalent to simple condition coverage. χ`Suds` also measures two data-flow coverage percentages, namely, "c-uses coverage," and "p-uses coverage". In this paper, we will measure all these four coverage percentages for ART and RT. Table II reports the number of program elements for each subject program. The values of N_s can be directly obtained from the χ`Suds` tool. It is an undecidable problem to automatically identify the program elements that are infeasible, that is, there does not exist an algorithm which can identify the infeasible program elements.

This study uses the following method to calculate N_i. 100,000 test cases are randomly generated and executed for each subject program. N_i is the number of the program elements that are not executed by any of these 100,000 test cases.

This study uses `Proteum` [16] to evaluate and compare the mutation scores of ART and RT. Given a C program, `Proteum` can create a set of mutants, execute them against test cases, and report the mutation score. `Proteum` provides 71 mutation operators which are classified into four classes: statement, operator, variable, and constant. All these operators are applied to create mutants of the subject programs, as summarized in Table III. It is also an undecidable problem to automatically identify the equivalent mutants. In this study, M_q is the number of mutants
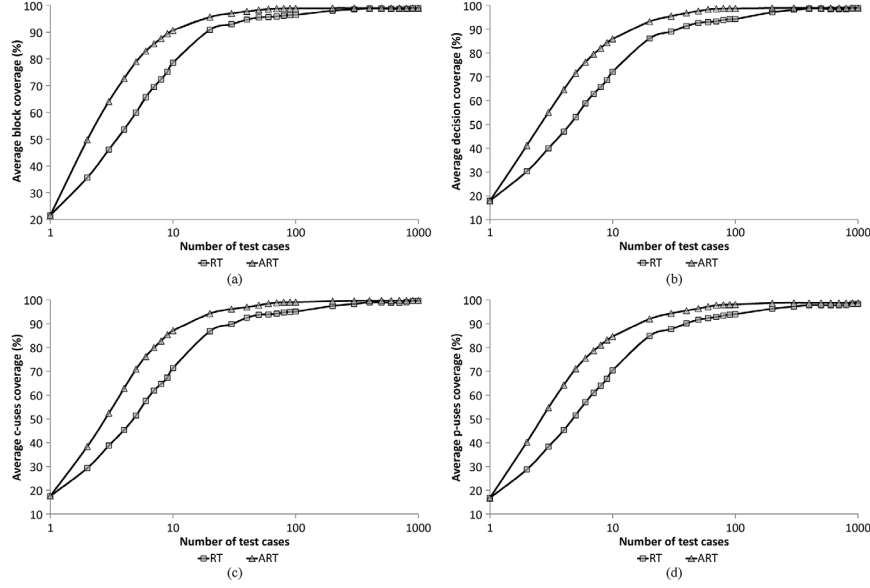
Fig. 9.   Coverage percentages of ART and RT on the program `Spline`: (a) block coverage on `Spline`; (b) decision coverage on `Spline`; (c) C-uses coverage on `Spline`; (d) P-uses coverage on `Spline`.

that are not killed by any of 100,000 randomly-generated test cases.

We evaluate the coverage percentages and mutation scores of ART and RT through the following four step procedure.

1) Choose a subject program, and a test case selection strategy.
2) Generate a test set, with the number of test cases (that is, the size of the test set) being $1, 2, \cdots, 10, 20, \cdots, 100, 200, \cdots, 1000$.
3) Use χ`Suds`, and `Proteum` to evaluate four coverage percentages, and the mutation score, respectively, of the test set generated in Step 2.
4) Repeat Steps 2 and 3 for a sufficient number (S) of times such that the mean value of the coverage percentages or mutation scores is statistically reliable within a certain confidence level $(1 - \alpha) \times 100\%$, and accuracy range $\pm r\%$. According to the central limit theorem [41], we can get

$$S = \left(\frac{100 \cdot \Phi^{-1} \left(\frac{2-\alpha}{2} \right) \cdot \sigma}{r \cdot \mu} \right)^2, \qquad (3)$$

where μ, and σ are the mean value, and the standard deviation of coverage percentages or mutation scores collected in Step 3, respectively; and $\Phi^{-1}(\cdot)$ denotes the inverse standard normal distribution function. In this paper, we set the confidence level, and the accuracy range as 95% $(\alpha = 0.05)$, and $\pm 5\% (r = 5)$, respectively.

We applied RT and ART to all ten subject programs. Because each of these programs reads in a list of arguments via the command prompt, a random test case can be generated by constructing a list of random arguments. Details of such a random generator can be found in the work of Wong *et al.* [45].

For all subject programs, our experiments use the category-partition-based metric introduced in Section II-B to measure the distance between two test inputs. To implement ART, we identified the categories and associated choices by examining the specification of each program. Some specifications are too brief, so we need to inspect the source code of some programs to get a full picture of the input-output relations.

In this study, the computation overhead of generating n test cases for RT, and ART are in $O(n)$, and $O(n^2)$, respectively. In our experiments, the number of test cases is not very large (maximum of 1000). Moreover, the time for collecting data on coverage percentages and mutation scores is much longer than the test case generation time. Therefore, there is no significant difference in testing time between ART and RT. As a reminder, we use the FSCS-ART algorithm (which requires $O(n^2)$ time to generate n test cases) to study ART in this paper. As discussed in Section II-A, there are other ART algorithms that have different computation overheads. For example, the algorithm of Random Border Centroidal Voronoi Tessellations [38] has the runtime in $O(n)$ for generating n test cases. Also note that extra efforts are required when applying RT and ART in real-life situations. For example, proper random test case generators should be used when RT is employed. In addition, categories and choices ought to be identified when implementing ART on programs with inputs of arbitrary types (as shown in Section II-B).

IV. CODE COVERAGE OF ADAPTIVE RANDOM TESTING

A. Comparison of ART and RT Based on Structure-Based Coverage

Figs. 2–11 compare the structure-based coverage percentages of ART and RT. In these figures, the x-axis represents the number of test cases in the logarithmic scale, and y-axis denotes the average coverage percentages achieved by ART and RT.

Based on the experimental data, we have the following observations.

- For programs `Cal`, `Checkeq`, `Col`, `Crypt`, `Look`, `Sort`, `Spline`, `Tr`, and `Uniq`:
  — When the size of the test set is small, ART has higher coverage percentages than RT.
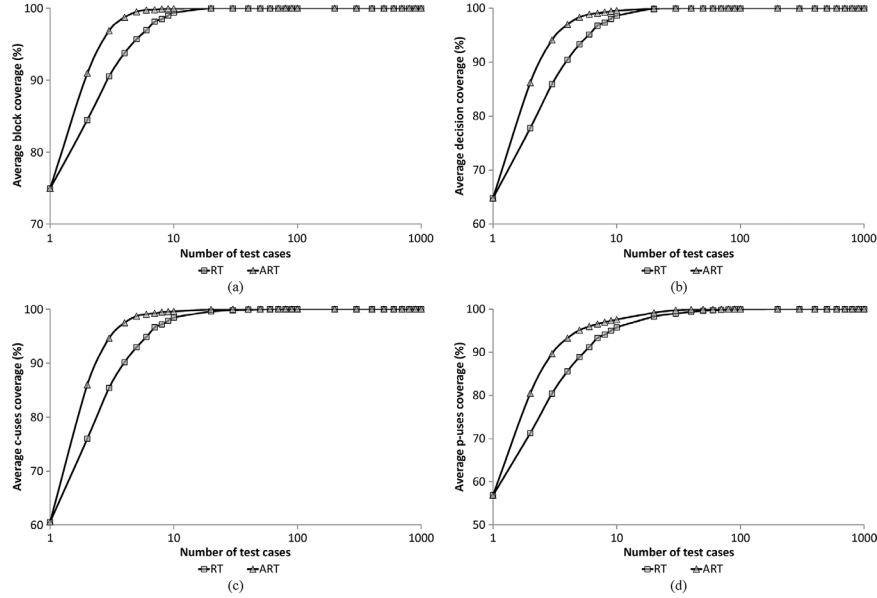
Fig. 10.   Coverage percentages of ART and RT on the program `Tr`: (a) block coverage on `Tr`; (b) decision coverage on `Tr`; (c) C-uses coverage on `Tr`; (d) P-uses coverage on `Tr`.
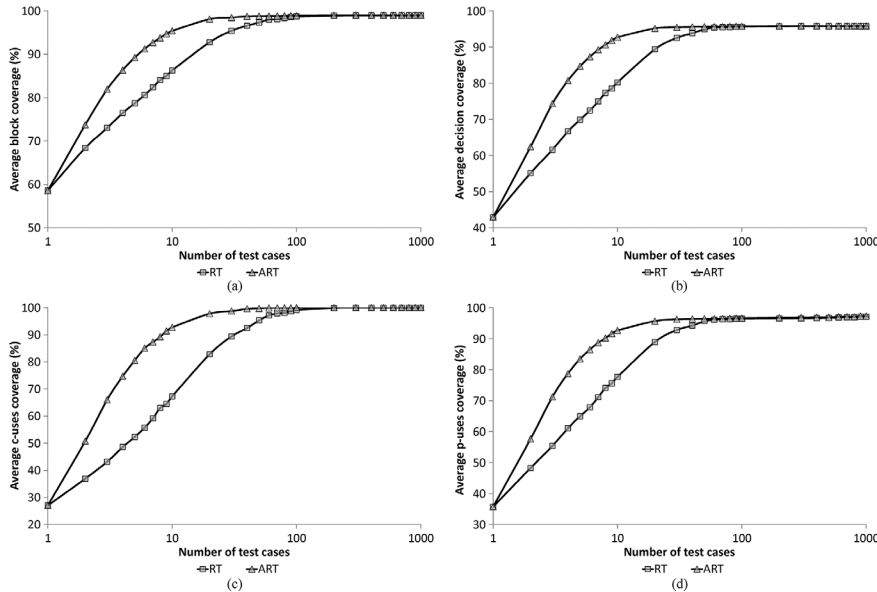

Fig. 11.   Coverage percentages of ART and RT on the program `Uniq`: (a) block coverage on `Uniq`; (b) decision coverage on `Uniq`; (c) C-uses coverage on `Uniq`; (d) P-uses coverage on `Uniq`.

— Under other situations, ART and RT have similar coverage percentages.
- For program `Comm`:
  — On block, decision, and p-uses criteria, when the number of test cases is very small or large, ART and RT have similar coverage percentages. Under other situations, ART has higher coverage percentages than RT.
  — On c-uses criterion, when the number of test cases is small, the coverage percentages of RT are marginally higher than those of ART. Under other situations, ART and RT have similar coverage percentages.

In summary, we observe that, other than one exception (c-uses for program `Comm`), ART has noticeable coverage improvement over RT starting from a small test set. On one hand, ART uses fewer test cases than RT to achieve the same coverage; on the other hand, ART attains a higher coverage than RT with the same number of test cases. When the size of the test set is large enough, most elements (such as blocks, decisions, c-uses, and p-uses) in the program have already been covered. Therefore, it is also understandable that the coverage percentages of RT are approaching those of ART with the increase of the number of test cases. Generally speaking, with the same number of test cases, ART is likely to cover the program under test more thoroughly than RT. In other words, ART is a better testing method than RT in terms of structure-based coverage. Thus, diversity across the input domain somehow incurs a higher structure-based coverage.
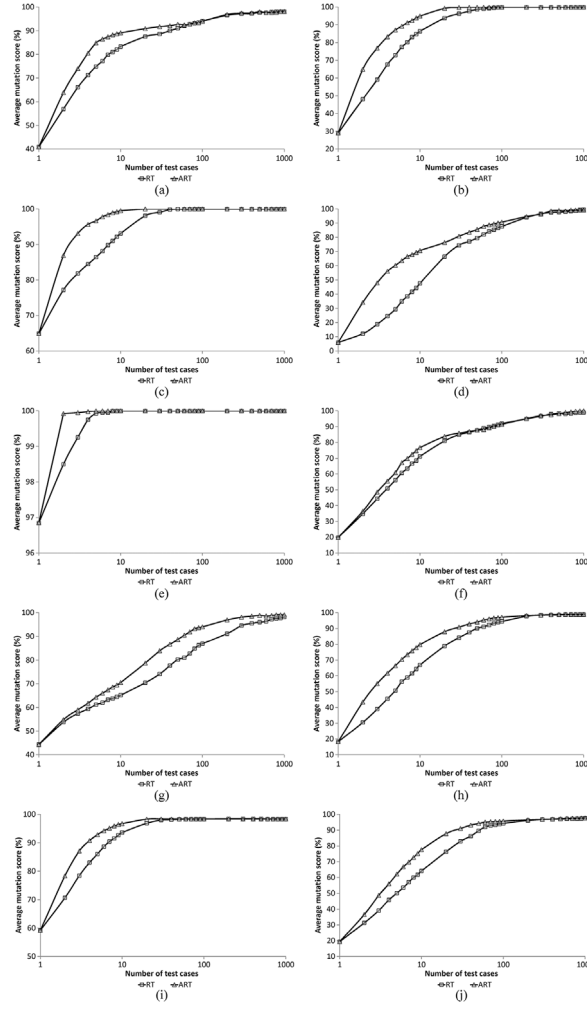
Fig. 12. Mutation scores of ART and RT: (a) mutation scores on `Cal`; (b) mutation scores on `Checkeq`; (c) mutation scores on `Col`; (d) mutation scores on `Comm`; (e) mutation scores on `Crypt`; (f) mutation scores on `Look`; (g) mutation scores on `Sort`; (h) mutation scores on `Spline`; (i) mutation scores on `Tr`; (j) mutation scores on `Uniq`.

B. Comparison of ART and RT Based on Fault-Based Coverage

The experimental results on mutation scores of ART and RT are reported in Fig. 12, where the x-axis represents the size of test set in the logarithmic scale, and y-axis denotes the average mutation scores.

From Fig. 12, the following can be observed.

- When the number of test cases is small, ART has higher mutation scores than RT.
- The mutation scores of RT are approaching those of ART with an increase of the number of test cases.
- When the number of test cases is large, ART and RT have similar mutation scores.

Similar to the results of structure-based coverage, ART is likely to kill more mutants than RT with the same number of test cases, which implies that ART usually has higher fault-based coverage than RT. As the size of the test set increases, most mutants can be killed sooner or later. Thus, it is not surprising that RT has similar fault-based coverage as ART when there are a large number of test cases. In a word, ART is better than RT with respect to the fault-based coverage.

V. THREATS TO VALIDITY

There are some potential threats to the validity of our study, as discussed in the following.

One major concern about internal validity is the implementations of the testing strategies. There might exist some errors when we implemented RT and ART. However, it should be pointed out that the size, and complexity of the implementations were very small, and low, respectively. The same implementations have been extensively used in the authors' previous studies [9], [11], [45], and we have carefully reviewed the code for its correctness. Another threat is that we identified the infeasible program elements and the equivalent mutants by executing 100 000 randomly-generated test cases. It is possible that some program elements or mutants were mistakenly classified.

There are also several threats to the external validity of this study. First, we selected ten UNIX utility programs as the subjects of our experiments. Although these programs have various characteristics, we should be careful when making a general statement that similar observations also apply to other types of programs. Secondly, the test case selection process depends on the knowledge and experience of the tester. For example, to

measure the distance, a tester needs to identify appropriate categories and choices for the program under test. Such an identification process is somewhat subjective, and may not be straightforward.

The threats to the construct validity are related to the measurement. In this study, we measured the code coverage of ART and RT based on five criteria. There are various coverage criteria in the literature [48]. For a test set that is regarded as adequate with respect to one coverage criterion, it may not be adequate in terms of another criterion. Having said that, the coverage criteria used in this study are representative, and commonly used in practice. Thus, our analysis is broad-ranged.

VI. CONCLUSION AND FUTURE WORK

RT is a popularly used technique for assessing software reliability. Its effectiveness in detecting software failures can be enhanced if test cases are evenly spread over the input domain. Such an intuition of "even spread" is the core of ART. Previous studies mainly focused on evaluating and comparing ART and RT in terms of their failure-detection capabilities, and it has been shown that ART usually has smaller F-measures than RT; that is, ART can detect the first software failure with fewer test cases than RT.

In this study, we conducted a series of experiments to compare the effectiveness of ART and RT from another perspective, the code coverage that they can achieve. We selected a particular ART algorithm, namely FSCS-ART, and measured its structure-based and fault-based coverage on ten UNIX utility programs. Because the subject programs have various types of inputs, a category-partition-based metric was applied to measure the distance among test cases. Aligning with our previous study[9], this paper shows that ART can achieve higher coverage on program structures, not only for programs with numeric inputs, but also for those with non-numeric inputs. Besides the higher structure-based coverage, this study also shows that ART normally kills more mutants than RT with the same number of test cases. In summary, ART is a more effective software testing method than RT, not only because of its smaller F-measures, but also because of its higher structured-based and fault-based coverage. By achieving higher coverage than RT with the same number of test cases, ART also improves the effectiveness of software reliability estimation, and increases our confidence in the reliability of the program under test even when no failure is detected.

In this paper, we investigated the code coverage of one ART algorithm, FSCS-ART. There are various ART algorithms in the literature, which evenly spread random test cases in different ways. It is interesting to measure and compare the code coverage achieved by different ART algorithms. It is also worthwhile to select more programs, especially those with a larger scale, and to conduct more extensive studies. Finally, there exist various metrics to measure the distance among test cases [14], [25]. Further work could be conducted to investigate to what extent various distance metrics can improve the code coverage of ART.

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