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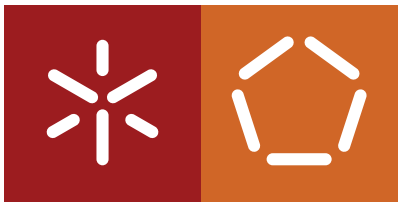

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AuTGen-C: a platform for automatic test data generation using CBMC

Master dissertation
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Dissertation supervised by
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ABSTRACT

The importance of good test cases is universally recognized and so is the high costs associated to their manual generation.

Software testing via coverage analysis is the most popular and used technique for software verification in industry but remains one of the most expensive tasks in the software development life cycle, since manual generation is often involved.

Mechanised verification techniques can have a role in the automated test generation, reducing the costs of the generation process and producing good quality tests. An example of this is the use of bounded model checkers of software for this purpose, having as flagship the CBMC tool for ANSI-C code. In Angeletti et al. papers [1, 2] it is described how CBMC was used as an automatic test data generator for coverage analysis of safety-critical software in an industrial setting. The motivation for this dissertation was to explore, implement, and extend the ideas presented in those works and to build an open-source tool for test data generation based on CBMC.

We have designed and implemented the AuTGen-C tool, a platform for the automatic generation of set of tests for C programs with high level of coverage (always trying to reach 100%), totally based on the CBMC tool.

A new technique was devised for instrumenting the code based on the introduction of fresh-variables that allows for a greater control over the process of test generation, and allows us to perform the coverage analysis based on the responses obtained from CBMC. Thereby, we avoid the use of an external tool to check the level of coverage achieved. Based on this technique, we have developed two different methodologies: the *fresh-variable methodology for single location*, which generates each test having as target a specific location of the code; and the *fresh-variable methodology for multi-locations*, which generates each test having as target a set of locations in the code. For the application of the later methodology we previously construct sets of locations that potentially can be reached in a single run of the program (i.e., that belong to some path). The motivation behind this ideia is to try to achieve the same coverage level with smaller test sets.

The methodologies implemented in the AuTGen-C tool are for the decision coverage criterion, but the same approach can be used for different criteria. In this dissertation we also discuss how those methodologies could be adapted to condition coverage and condition/decision coverage criteria.

The AuTGen-C tool is available and ready to be used. We experimentally evaluated the effectiveness of the AuTGen-C tool by running it over several case studies including the popular open-source application `grep`. These preliminary experiments were very encouraging.

RESUMO

O teste de software baseado na análise de cobertura do código é uma técnica muito utilizada para a verificação de software na indústria, mas continua a ser um dos processos mais caros do seu desenvolvimento visto que a geração de bons casos de teste é por vezes um processo manual.

As técnicas de verificação automática de software podem ter um papel na automatização do processo de geração de testes de qualidade, reduzindo muito os custos associados à sua produção. Um exemplo disso é a utilização para este fim de *software bounded model checkers* (de onde se destaca a ferramenta CBMC para verificação de código C). Angeletti et al. descrevem em [1, 2] uma aplicação com elevado sucesso do CBMC na geração automática de testes com alta taxa de cobertura, no contexto industrial do sistema europeu de controlo de linhas ferroviárias. A motivação para esta dissertação foi explorar, implementar e extender as ideias apresentadas nesses trabalhos, e construir uma ferramenta (de código aberto) para geração automática de testes baseada no CBMC.

No âmbito deste projecto desenvolvemos a ferramenta AuTGen-C, uma plataforma para a geração automática de testes, para programas C, com um nível muito elevado de cobertura (tentando sempre atingir 100%), totalmente baseado na ferramenta CBMC. Desenvolvemos uma nova técnica de instrumentar o código, com base na introdução de *variáveis novas*, que nos permite um maior controle sobre o processo de geração de testes e nos possibilita fazer a análise de cobertura com base nas respostas obtidas do CBMC, evitando assim a utilização de uma ferramenta externa. Com base nesta técnica, desenvolvemos duas metodologias diferentes para a geração de testes: uma metodologia que se foca *num único local do código* de cada vez que se gera um teste; e uma outra metodologia que tem como alvo *um conjunto de locais do código* que são previamente calculados de forma a que tenham potencial para serem cobertos por um único teste. A motivação para esta segunda metodologia é tentar alcançar um elevado nível de cobertura com um conjunto mais reduzido de testes. Discutem-se também como estas metodologias podem ser aplicadas para outros critérios de cobertura. Por fim é feita uma avaliação experimental da ferramenta AuTGen-C aplicando-a a vários casos de estudo incluindo à popular aplicação `grep`. Os resultados que obtivemos foram bastante encorajadores.

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INTRODUCTION

1.1 MOTIVATION

Nowadays it is increasingly important to ensure quality in the produced software. Defects in software result in high costs and operational inefficiencies. Software testing is the technique embraced by the software industry to certify and ensure quality in software products. Fifty percent of the development time and between thirty four up to fifty percent of the total costs are related to software testing. These percentages have not changed along the years [17], which indicate us that there is some progress that can be made.

Failures due to software defects may have serious consequences. An emblematic case with serious consequences was the multiple failures in the automated baggage system due to software errors at Denver International Airport [12]. The software errors in the system had initially delayed the airport inauguration by 16 months and after eleven years of unreliable service, the automated baggage handler had to be pluged-out and converted into a traditional service using manual carts and tugs with human drivers.

What happened at Denver International Airport is not an isolated case. A report presented by Tassey [24] in 2002 indicates that national annual costs due to inadequate software testing was estimated to range from $22.2 to $59.5 billion only in the United States of America. Among the contributing factors are under-budget test resources, inadequate methods, tight schedules, poor requirements design, low level testing, poor test management, unskilled/untrained testers and inadequate use of automated testing tools.

High costs in software production normally comes from defects that are discovered in later stages of software development. Several studies [19, 20, 22] reported the costs associated to the repair of software escalates enormously from phase to phase. Reasons that can justify such behaviours are related to defects that propagate through the software life cycle resulting in an expensive and time-consuming redesign which by itself creates new defects.

Certification and quality is crucial when the topic is critical software. A software system is considered critical if it may cause severe injury to human lives or occupational illness, and/or major damage to facilities, systems, or hardware [21]. A common regulatory feature of all safety-critical software standards is that software must demonstrate, through rigorous testing and documentation that it is well

designed and operates safely. Testing of safety-critical software includes code coverage and analysis to insure that all program instructions are tested. This requirement substantially increases the costs associated to testing task since it often involves the manual generation of tests.

Testing has been the primary way that software is checked for correctness. However testing requires substantial resources and can rarely check all possible execution scenarios. Tests are usually created based on the most likely usage of the software or on intuition where a bug may lie. This often results in undetected errors. Another way to guarantee the correctness of software is by using program verification techniques. There are different approaches to program verification. The deductive approach is based on the use of a program logic and the design-by-contract principle, and it allows for expressing properties using a rich specification language. However deductive verification lacks automation - tools for deductive verification requires a lot of human intervention and working with them is a very specialised job and may require a lot of effort.

Another approach to program verification is based on model checking and abstraction techniques. Model checking of software, which typically allows only for simpler properties, expressed as assertions in the code, but is fully automated. The fundamental idea is to create a model from the source program, and then, given a property, to check if it holds in that model. However, such an approach has a main downside: state space explosion. Existential abstraction [8] and bounded model checking [5] are two approaches that can be used to overcome this limitation. The former is a conservative technique: it introduces false positives (false warnings), sacrificing completeness, while the latter technique only checks execution paths with size up to a fixed (user-provided) bound, sacrificing soundness. The false positives introduced by abstraction techniques must be manually filtered from the real bugs and can become an overwhelming task. The soundness of the bounded model checking technique can be regained by conservatively introducing special "unwinding" assertions to check that longer execution paths cannot occur during execution of the program, but the general idea is that only a partial exploration of the state space is performed.

Despite the enormous improvements in verification tools in the last decade, their use in the verification of software with some complexity may have high costs. This fact has made verification accessible to only the most safe-critical software and not to most commercial software.

The importance of good test cases is universally recognized and so is the high cost of generating them by hand. Mechanized verification techniques can have a role in the automated generation of tests. In the recent years, testing and verification have come close together.

An example of this is the use of bounded model checkers of software, having as flagship the CBMC tool [7] for ANSI-C code. The key idea of bounded model checking of software is to encode bounded behaviours of the program that enjoy some given property as a logical formula whose models, if any, describe execution paths leading to a violation of the property. The properties to be established are assertions on the program state, included in the program through the use of assert statements. For every execution of the program, whenever a statement `assert` ϕ is met, the assertion ϕ must be satisfied by the current state, otherwise we say that the state violates the assertion ϕ. The verification

technique assumes that a satisfiability-based tool is used to find models corresponding to property violations.

This technique can be very helpful in finding inputs that make the program execute some improvable path where a bug may be hidden. These kind of bugs are rarely discovered by pure directed testing algorithms. Rather than demonstrating program correctness, the focus of this technique is finding bugs in real-world programs. The ability to express properties as assertions, and to return an assignment to input variables falsifying the property make bounded model checking of software particularly tailored to automatic test data generation.

In Angeletti et al. [2] it is described how CBMC has been used for coverage analysis of safety-critical software in an industrial setting. In particular, they experimented CBMC on a subset of the modules of the European Train Control System (ETCS) of the European Rail Traffic Management System (ERTMS) source code, an industrial system for the control of the traffic railway. The methodology they proposed was applied to the ERTMS/ETCS, with thousands of lines, obtaining a set of tests that covers 100% of the code coverage, requested by the CENELEC EN50128 guidelines for software development of safety critical systems.

In another paper [1] Angeletti et al. present a new methodology for the automatic test data generation based on the use of CBMC, with the aim of improving the quality of the test set generated, in the sense of avoiding the production of redundant tests i.e. the test generation of tests that do not contribute to reach the property of 100% of code coverage. Indeed, these redundant tests are useless from the perspective of the coverage, and they are not easy to detect and to remove a posteriori, and, if maintained, imply additional costs during the verification process.

The tools described in the Angeletti et al. papers are not available for public usage. The motivation for this dissertation was to explore, implement, and extend the ideas presented in those papers and to build an open-source tool for test data generation based on CBMC.

1.2 Contributions

The main contribution of this dissertation is the design and implementation of the AuTGen-C tool, a platform for the automated test data generation for C programs with a very high level of coverage (100% if possible), totally based in the CBMC tool. The AuTGen-C tool is open source, and can be obtained in `https://bitbucket.org/Esteves/autgen-c`.

We began by implementing the technique described in [2] but without using an external tool for the coverage analysis step (as it is done in the original work), because we did not find a freeware tool suiting our purpose. Without having the tools to do the coverage analysis, the only way to guarantee that we reach the highest level of code coverage with the generated tests is by having a high degree of redundancy - a test is generated for each location.

To overcome this difficulty we invented a new technique based on the introduction of fresh variables to signalise the various points in the code required to be reached by the code coverage criterion. This

technique, in addition to allow greater control over the process of test generation, allows us to perform the coverage analysis based on the responses obtained from CBMC, thereby avoiding the use of an external analysis tool.

Based on this technique, we have developed two different methodologies: the fresh-variable methodology for single location which generates tests having as target a specific location of the code, and the fresh-variable methodology for multi-locations which generates tests having as target a set of locations in the code. For the application of the later methodology we previously construct sets of locations that potentially can be reached in a single run of the program. The motivation behind this idea is to try to achieve the same coverage level with a smaller set of tests.

The methodologies implemented in the AuTGen-C tool are for the decision coverage criterion, but the same approach can be used for other coverage criteria. In this dissertation we also discuss how those methodologies could be adapted to condition coverage and condition/decision coverage criteria.

1.3 Document Structure

The rest of the dissertation is organized as follows. Chapter 2 gives an overview of software testing and describes precisely the different criteria of code coverage.

Chapter 3 is devoted to bounded model checking of software and its use in automatic test data generation. The first part of the chapter describes the necessary transformations to perform bounded model checking of software, detailing all the steps involved in the extraction of a logical model from a program. In the second part we descrive the ideas presented in [1, 2] for the automatic test data generation based on the use of CBMC.

Chapter 4 is devoted to the description of the techniques and methodologies developed by us and implemented in the AuTGen-C tool. We describe two different techniques for signalling locations in the code: the first one following the ideias described in Chapter 3 and then a new technique that we designed to overcome the problems found in the first. Based on those techniques, we then explain the three methodologies developed for decision coverage. Finally, we discuss how the condition coverage and condition/decision coverage criteria could also be achieved.

Chapter 5 focuses on the implementation of the AuTGen-C tool. We present the architecture of the tool and its implementation details. We discuss the design choices, how we have implemented the key topics described in the previous chapters, the challenges founded and the solutions for those challenges. We end the chapter with a mini-tutorial about the tool usage.

Chapter 6 is devoted to the evaluation of the AuTGen-C tool, and to present some conclusions about the work developed. We perform an empirical study comparing the different methodologies implemented in the tool using several case studies. We analyse the results obtained and the performance of the tool, and then we conclude and point out some directions for future work.

2

BACKGROUND

In this chapter we give an overview of software testing and some basic concepts that we use throughout this document. We focus on description of the different code coverage criteria and its advantages and disadvantages.

2.1 An Overview in Software Testing

Software testing scope and goals changed over the time. Initially it started as a debugging method to reveal errors and evolved into guarantee the quality in the software being test. Nowadays, software testing is a vast area containing a large number of techniques and several criteria to categorize them.

2.1.1 *Software Testing Over Time*

Throughout time software testing was looked upon different perspectives. Gelperin and Hetzel in [9] classified and delimited different periods of software testing by scope and goals over time. Until 1956 there was no clear difference between testing and debugging: it was the *debug-oriented period*. 1957-1978 is classified as the *demonstration-oriented period*, where "make sure the program runs" and "make sure the program solves the problem" defined the software testing process. 1979-1982 is named *destruction-oriented period*, where testing was understood as "the process of executing a program with the intent of finding errors". 1983-1987 is called the *evaluation-oriented period*, characterised by the introduction of methodologies (such as analysis, reviews and test activities) during all the software development cycle to provide product evaluation. In 1988 we entered in the *prevention-oriented period*, where the testing process is more professional and aims not only the detection and prevention of faults but also that software satisfies its requirements. In [9] the authors highlight the creation and use of methodologies that define the software testing tasks to take place parallel to the development of the code.

Gelperin and Hetzel was published [9] in 1988 and it is our opinion that the last period defined by them as already passed. Nowadays, software testing is seen as "The process of revealing defects in the code with the ultimate goal of establishing that the software has attained a specified degree of quality"[11].

2.1.2 *Levels of Software Testing*

Nowadays, software testing is seen as part of software development and it is divided in different levels. The most common levels are *unit*, *integration*, *system* and *acceptance*. Each level has its own purpose and they are performed in sequence. Automated test data generators can be generate from unit level to system level, but they normally are more used in the unit level for scalability reasons.

Unit Testing

Unit testing is a level of software testing process where individual units are tested. The purpose of unit tests is to validate that each unit performs as designed. In other words, if they are fit for use.

Even though a unit is considered to be the smallest testable part, in the test generation community, when it comes to define this part there is not a common opinion. For some it could be a simple function but for others it could be a set of functions or even the whole module.

Integration Testing

Integration testing is a level of software testing process with the objective to identifies problems that occur when units are combined. In other words, units that had already been tested are now combined as one component and then is tested the interface between them. The integration testing proceeds the unit testing.

There is two different approach when applying the integration test. The top-down and the bottom-up. Also exists some references to a third one, the umbrella approach.

- *Top-down:* "The top-down approach to integration testing requires the highest-level modules be test and integrated first. This allows high-level logic and data flow to be tested early in the process and it tends to minimize the need for drivers. However, the need for stubs complicates test management and low-level utilities are tested relatively late in the development cycle. Another disadvantage of top-down integration testing is its poor support for early release of limited functionality."[16]

- *Bottom-up:* "The bottom-up approach requires the lowest-level units be tested and integrated first. These units are frequently referred to as utility modules. By using this approach, utility modules are tested early in the development process and the need for stubs is minimized. The downside, however, is that the need for drivers complicates test management and high-level logic and data flow are tested late. Like the top-down approach, the bottom-up approach also provides poor support for early release of limited functionality."[16]

- *Umbrella:* "The umbrella approach requires testing along functional data and control-flow paths. First, the inputs for functions are integrated in the bottom-up pattern discussed above. The outputs for each function are then integrated in the top-down manner. The primary advantage of

this approach is the degree of support for early release of limited functionality. It also helps minimize the need for stubs and drivers. The potential weaknesses of this approach are significant, however, in that it can be less systematic than the other two approaches, leading to the need for more regression testing."[16]

System Testing

System testing is the level of software testing process where the behaviour of whole system/product is tested, to verify the system meets the specification and its purpose. It is is carried out by specialists testers or independent testers and should investigate both functional and non-functional requirements of the testing.

Acceptance Testing

Acceptance Testing is a level of the software testing process where a system has met the requirement specifications, and now will be the tested for acceptability. The main purpose of this test is to evaluate the system's compliance with the business requirements and verify if it has met the required criteria for delivery to end users. This should be fulfilled by elements that are not the coders of the software.

The acceptance testing can be divided in two major steps normally referenced as *alpha testing* and *beta testing*.

- *Alpha Testing:* The Alpha testing is when the acceptability are realized by the programmer with direct knowledge of the code but not involve in their development. The primary objective in this phase is the validation tests realized by the coder team.

- *Beta Testing:* The Beta testing is when the acceptability are realized by the customer side, It involves testing by a external group formed by customers or possible future users who use the system at their own locations and provide feedback. This append before the system is released to customers.

2.2 Code Coverage

Code coverage is a measure for describing the degree to which the source code of a program is tested by a set suite. It is a quality assurance metric which determines how exhaustively a set of tests exercises a given program.

The coverage criteria establish the rules a test suite needs to satisfy. The percentage of code exercised by a test suite is measured according to such criteria. There are many different criteria such as: statement coverage, decision coverage, condition coverage, multiple condition coverage, condition/decision coverage and modified condition/decision coverage, among others. Next we will give a description of such code coverage criteria.

```
void foo(int A,int B,int X) {
  if(A>1 && B==0) {
    X=X/A;
  }
  if(A==2  || X>1) {
    X=X+1;
  }
}
```

Figure 1 Foo function

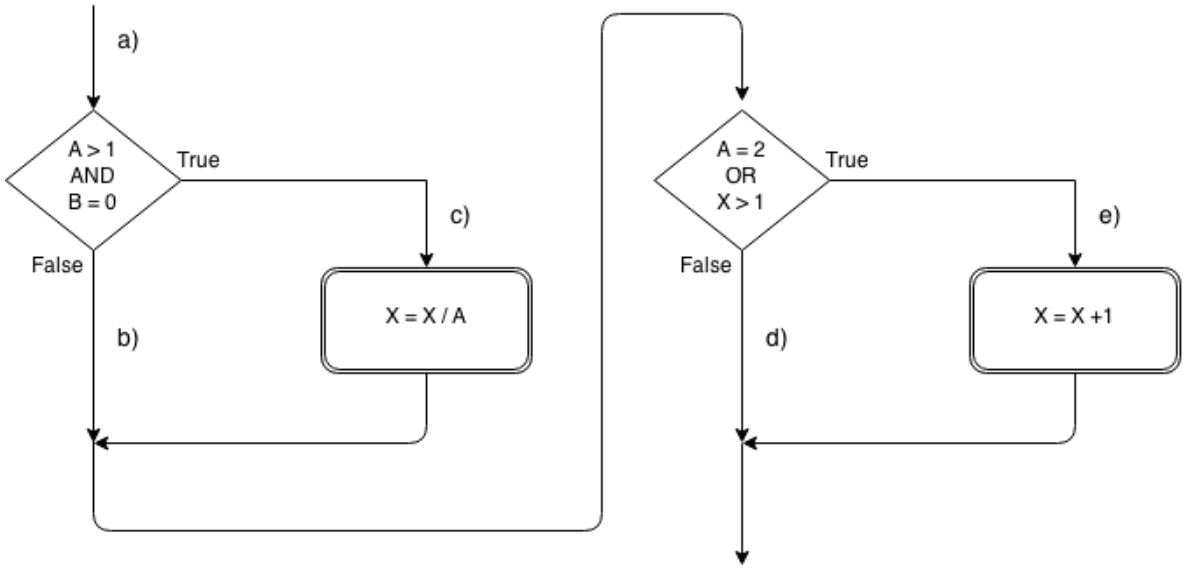

Figure 2 Control flow graph of the function in Figure 1

2.2.1 *Statement Coverage*

> *Statement Coverage* criterion states that one must write enough tests so that every statement in the program must be executed at least once.

Consider the function in Figure 1 and its control flow graph in Figure 2. If we want to generate the necessary set of tests to achieve statement coverage for the code presented in Figure 1, the test vector$A = 2,\ B = 0,\ X = 3$ is the only test necessary to achieve this criterion. The execution of this test passes throughout all the statements and follows the path *ace* in graph in Figure 2.

Considerations when applying this criterion

This criterion is consider rather weak and generally useless[17]. Considering the previous example, the path *abd* where X is kept unchanged will never be executed. The reason why this happens is because there exist no statement throughout the path *abd*, so if there is any error it would go unnoticed.

2.2.2 *Decision Coverage or Branch Coverage*

> *Decision Coverage* criterion states that every decision in the program must take all possible outcomes at least once, and every entry and exit point in the program has been invoked at least once.

To achieve full decision coverage for the code in Figure 1, it is enough to generate a set of tests for the paths (ace, abd) or for the paths (acd, abe) from Figure 2. In both cases the paths pass throughout all decisions in the program obtaining true and false outcome.

Considerations when applying this criterion

Although decision coverage criterion is considered a stronger criterion than statement coverage criterion, it is viewed as rather weak. It exists a probability of 50 percent that the path where variable X is unchanged, the abd path, will not be considered.

Consideration when defined this criterion

There is no clear consensus in the testing community when it comes to define decision or branch coverage. In the following paragraphs we present different definitions for decision or branch coverage.

The authors of [17] initially described this coverage criterion as "Must be written enough test cases that each decision has a true and a false outcome at least once", however, the authors rewrites the definition after comparing it with the statement coverage. The authors affirms that decision coverage is superior to statement coverage and, therefore, the decision coverage must also contemplate the cases coverage by the statement coverage criterion. The new definition provided by the authors to decision coverage is "Decision coverage requires that each decision have a true and a false outcome, and that each statement be executed at least once." or "An alternative and easier way of expressing it is each decision has a true and a false outcome, and that each point of entry be invoked at least once."

Other definition for the decision coverage is presented by Kelly J. et al. [15] which defines decision coverage criterion as "Every decision in the program has taken all possible outcomes at least once and every point of entry and exit in the program has been invoked at least once.".

Also Naik and Tripathy [18] defines differently the decision coverage criterion. Citing the author (that uses the term branch coverage instead of decision coverage), derision coverage criterion is "Selecting program paths in such a manner that certain branches (i.e., outgoing edges of nodes) of a control flow graph are covered by the execution of those paths. Complete branch coverage means selecting some paths such that their execution causes all the branches to be covered".

If we had only defined the decision coverage as "Every decision in the program has taken all possible outcomes at least once", it would exist examples of code where no tests would produced. For instance, the code shown in Figure 3 does not have any decision, therefore, no tests would be generated. Requiring also that every entry point in the program be invoke at least once solves this problem.

```
void foo(int A,int B,int X) {
  A=A+1;
  B=A;
}
```

Figure 3 Code example with no decision

Another solution would be require that every exit point in the program be invoke at least once. Moreover, it would also allows to identify some cases of dead code. For instance, in the program of Figure 4, the code after the `return A` statement would be identified as dead code.

```
int foo(int A,int B,int X) {
  ...
  return A;
  A=A+1;
  B=A;
  return B;
}
```

Figure 4 Code example with no decision

The C language do not allows functions with multi-entry points. Thereby, the criterion "Every decision in the program has taken all possible outcomes at least once and every exit point in the program has been invoked at least once" is enough to achieve the same paths as the criterion "Every decision in the program has taken all possible outcomes at least once and every point of entry and exit in the program has been invoked at least once".

2.2.3 *Condition Coverage*

> The *condition coverage* criterion states that each condition in a decision must take all possible outcomes at least once and every entry and exit in the program must be least once.

Considering the code listed in Figure 1 the minimum number of tests needed to achieve this code coverage criterion is only two. Using only this two tests $\{(A=2, B=0, X=2), (A=1, B=1, X=1)\}$ is possible to reach 100% of condition coverage. Note that in the present example, for both tests, the first decision is always true and the second decision is always false.

2.2.4 *Decision/Condition coverage*

> *The decision/condition coverage* criterion requires that each condition in a decision takes on all possible outcomes at least once, each decision takes on all possible outcomes at least once, and each entry point and exit point is invoked at least once.

To completely achieve decision/condition coverage for the code in Figure 1 the set of tests $\{ \ (A = 2, B = 0, X = 4), (A = -1, B = -1, X = -1) \ \}$ is enough. All condition are evaluated to true and to false, and the decisions are also evaluated to true and to false.

This criterion is a merge of decision coverage and condition coverage. The objective is to overcome some limitations found in both criteria.

2.2.5 *Modified Condition / Decision Coverage*

> The *modified condition/decision coverage* criterion states that every entry and exit point in the program has to be invoked at least once, every condition in a decision in the program has to take take all possible outcomes at least once, and each condition in a decision has to be shown to independently affect that decision's outcome.

The criterion improves the condition/decision coverage by requiring that each condition independently affect the outcome of the decision. The application of this criteria to the code in Figure 1 could be achieved with the following tests$\{(A = 2, B = 0, X = 2), (A = 1, B = 1, X = 1), (A = 0, B = 0, X = 2)\}$.

Considerations when applying this criterion

The generation of tests according to modified condition/decision coverage is more complex comparatively to condition/decision coverage. In the following lines we describe in detail how to generate the necessary tests to this criterion.

```
if (A && B && C) {
  ...
}
```

Figure 5 Conjunctions

```
if (A || B || C) {
  ...
}
```

Figure 6 Disjunctions

The decisions formed by an *and* operator or by an *or* operator are generated differently. A condition is shown to independently affect a decision outcome by varying just its value while keeping fixed the value of all the others conditions.

Following the nature of *and* operator, to ensure a condition is independently affecting the decisions outcome, the condition must be set to false and all the remaining conditions set to true. So the set of tests necessary to achieve the modified condition in Figure 5 is the set of tests $\{(A = False, B = True, C = True), (A = True, B = False, C = True), \ (A = True, B = True, C = False)\}$. But to achieve the modify condition/decision coverage it is also needed to add the test $(A = True, B = True, C = True)$ to obtain all possible decision outcomes.

Relative to the *or* operator, to ensure a condition is independently affecting the decisions outcome, the condition must be set to true and all the remaining conditions set to false. So the set of tests

necessary to achieve the modified condition in the code in Figure 6 is the set $\{(A = True, B = False, C = False), (A = False, B = True, C = False), (A = False, B = False, C = True)\}$. But to achieve the modify condition/decision coverage it is also needed to add the test $(A = False, B = False, C = False)$ to obtain all possible decision outcomes.

2.2.6 *Multiple Condition Coverage*

> The *multiple condition coverage* criterion states one must write a sufficient number of test cases to invoke all possible combinations of condition outcomes in each decision, and all points of entry to the program, at least once.

In other words, for a decision with n inputs the multiple condition coverage requires 2^n tests.

3

TEST DATA GENERATION USING BOUNDED MODEL CHECKING

Model checking is a verification technique that explores all possible system states a in brute-force manner. In this way, it can be shown that a given model satisfies certain properties [3]. When applied to software, model checking can be defined as an analysis algorithm that proves properties over program executions [13]. One of the disadvantages of this technique is the exponential growth in the number of states. Such is due to several factors, such as the number of variables or their representation size, which makes models too large for the current available resources. In an attempt to avoid the growth in the number of states a new technique called bounded model checking was introduced in 1999.

Bounded model checking was introduced in Biere et al. [5] for LTL (Linear temporal logic) through propositional decision procedures. Linear temporal logic is modal temporal logic widely used at the time to prove properties about programs since it allows to write formulas about the future of paths. Later this technique was extended to software. First developments in software bounded model checking initiated around the year 2004 and published in Clarke et al. [6, 7]. Clarke et al. presented in [7] the first bounded model checker targeting exclusively ANSI-C programs where properties to be verified were established through assertions and assumptions on the program as special statements.

In a simple way, bounded model checking is the same as model checking but the model being checked is bounded. In software bounded model checking, the model is the software and the bound is established by unwinding the loops a finite number of times. The bounded model is then transformed into propositional formulas which are used to prove the validity of the properties that we want to prove. The correctness obtained when applying this technique is ”partial” in the sense that the model being verified is not the original one, but only a part of it. This technique only checks executions with length up to a fixed (user-provided) bound, sacrificing soundness. However ”total” correctness is possible to achieve if we considered a bound that captures all possible execution behaviours. This can be consider as a disadvantage due to the general unsoundness of the approach, but on the other hand can be consider a advantage in finding counterexamples for the properties we want to check. For this reasons bounded model checking is often used as a bug finder.

Bounded model checking of software has also been applied in the field of automated test generation. In [2], Angeletti et al. reported a methodology to automatically generate coverage tests to ANSI-C

programs with high degree of coverage. In other paper [1], the same authors present a different strategy to automatic generate tests and overcome some issues from the previous technique.

In the following sections is discuss in greater detail the bounded model checking of software technique and its use in the field of automated test generation.

3.1 Software Bounded Model Checking

The bounded model checking technique as been largely used in detecting underflow and overflow, pointer safety, memory leaks, array bounds among others. This section is dedicated to explain the work-flow of software bounded model checking. In the following subsections we explain how users can insert their own properties, what should be expected from bounded model checking and how properties are verified. All the following subsections are based on [3, 5, 6, 7].

3.1.1 *Inserting Specific Properties*

Bounded model checking tools are fully automatic. They provide safe properties automatically, but users may annotate the code with properties they want to check. Manual annotations of properties normally are used for for debugging purposes or to check functional properties. In this dissertation we will use specific properties to obtain specific counterexamples which are then used as test to reach a certain coverage criteria. This specifications are normally introduced through statements in the source code, that are ignored by the compiler.

The standard annotations in bounded model checking of software are *assert* and *assume*.

```
if( A || B ) {
  assert(A==true);
  ...
}
```

Figure 7 Code example with assert statement with if statement

The properties we want to verify and expect to always be true are included through the use of assert statements. For every execution of the program, whenever a statement $assertp$ is met, the property p must be satisfied by the current state, otherwise we say that the p was violated. When a violation is found a counterexample is returned to the user. Generally when a bounded model checker finds an assertion violation, it immediately returns the counterexample and ignores forward assertions. Such action derives from the nature of SAT solvers. An example of the use of this mechanism is Figure 7 where it is checked if the condition A is always true using the property "$A == true$".

The annotation *assume* p, where p is a property, is used when the user wants to impose that only the executions satisfying p, at that location, are considered during the verification. In other words, whenever an *assume* p is annotated in the code, one wants to restrict the model being verified.

```
assume (A||B == true);
if( A ||  B ) {
  ...
}
```

Figure 8 Code example with assumption statement with if statement

An example in the use of this mechanism is Figure 8, where the model was restricted to traces passing through the true branch of the if condition, at that point, by using "$A||B == true$" property.

Is import to note that assumptions affect the evaluation of the assertions that occurs after them, in the sense that an assertion is implied by all previous assumptions. That can lead to a model so restricted that there are not any trace to be test and every assert will be vacuously true.

3.1.2 *The Bounded Model Checking Technique*

The Bounded Model Checking technique is divided into several steps. Their main goal is to transform a program into logical propositions to be checked by a SAT solver.

First, it is applied a process of simplification and transformation of the original program. That includes the elimination of directives(#*define*, #*include*, #*ifdefine*, etc..) and side-effects(*i*++,- -*i*, etc...) but also, if intended, the normalization of the program into a subset of the target programming language. An example of transformation process is show in Figure 9.

```
for(i=0;i <= max;
      i++) {
  x=5+(++j);
  ...
}
```

$\Rightarrow$

```
i=0;
while(i <= max) {
  j=j+1;
  x=5+j;
  ...
  i=i+1;
}
```

Figure 9 Normalization to a subset of instructions

Secondly, an automatic instrumentation process might be applied to the code. This step is optional. The user may want to check only its own properties. The properties automatically inserted are normally related to safely violations, such as overflow/underflow, array out of bounds, null pointers, dereferences, divisions by zero, among others. An example of automatic instrumentation is represented in Figure 10, where safety properties, related to array out bounds, are introduced in order to check if the values of i and max always lie in the array bounds. Also safety properties related to overflow are inserted to check if the operation $i+1$ does not cause an overflow. The predicate $!overflow$ is used because the encoding of this property might be different depending on the variable type, the minimum and maximum values are different, and the back-end solver.

```
max=0;
i=1;
while(i<max_array){
  if(a[i]>a[max]) max=i;
  i=i+1;
}
```

⇒

```
max=0;
i=1;
while(i<max_array){
   assert(i>=0 && (i<max_array);
   assert(max>=0 && (max<max_array);
   if(a[i]>a[max]) max=i;
   assert(!overflow(int,+,i,1);
   i=i+1;
}
```

Figure 10 An automatic instrumentation.
Array bounds for i and max. Overflow in variable i.

The next step is crucial. Then the programming is unwound a k number of times. The unwinding number k might be inferred automatically, when possible, or else, specified by the user. Loop constructs, function calls and backwards goto statements are the elements that are unwound.

Loop constructs can be expressed as while statements so all loop constructs are transformed into while statements, if not already a while statement, and unwound by duplicating the loop body k times. See Figure 11.

```
while(b){
  loop_body;
}
```

```
if(b){
  loop_body;
  if(b){
    loop_body;
    assert(!b);
  }
}
```

```
if(b){
  loop_body;
  if(b){
    loop_body;
    assume(b);
  }
}
```

Figure 11 In the left, the code to be unwind. In the right, the code with unwind assumption.
In the center, the code with unwind assertion.
The loops are unwound with a bound of 2.

Each copy is guarded using an if statement that uses the same condition as the loop statement. Such is for the case that the loop requires less than k iterations. After the last copy, an annotation with the negation of the loop condition is added. According to the annotation used, assertion or assumption, is called unwinding assertion or unwinding assumption. The unwinding assertion is used to know if k bound is actually large enough for any possible execution. If it is not large enough the loop assertion will fail. An alternative to the unwinding assertion is the use of unwinding assumption. When the unwinding assumption is used, then every path that requires more then k iterations will not be taken into account. An example of unwinding a loop twice is shown in Figure 12 and in this case was used an unwinding assertion.

Backwards goto statements are unwound in a manner similar to while loops. Function calls statements are replaced by the function body, variables are renamed to avoid conflicts between variables,

```
max=0;
i=1;
while(i<max_array){
  assert(i>=0 && (i<max_array);
  assert(max>=0 && (max<
      max_array);
  if(a[i]>a[max]) max=i;
  assert(!overflow(int,+,i,1);
  i=i+1;
}
```

⇒

```
max=0;
i=1;
if(i<max_array){
  assert(i>=0)&&(i<max_array);
  assert(max>=0)&&(max<max_array);
  if(a[i]>a[max]) max=i;
  assert!overflow(int,+,i,1);
  i=i+1;
  if(i<max_array){
    assert(i>=0)&&(i<max_array);
    assert(max>=0)&&(max<max_array);
    if(a[i]>a[max])max=i;
    assert!overflow(int,+,i,1);
    i=i+1;
    assert (!(i<max_array));
    }
  }
}
```

Figure 12 An unwinding assertion transformation from Figure 10

and the return statement is replaced by an assignment, if it returns a value. Also if the function is recursive then it is handled in similar way to while loops. It is linked k times and unwinding assertion or unwinding assumption is used.

At this point, the program consists only of if statements, assignments, assertions, labels, and forward goto statements. As logical variables are immutable (variables are assigned at most once). To transform the program into logical formulas it is required that program variables to be also immutable. To accomplish this, it is necessary to transform the program into a single assignment form. Exists two different techniques to apply single assignment, the dynamic and static. The static single assignment renames all variables so each variable is assigned exactly once. The dynamic single assignment comparatively to static single assignment do the same but reuse some variables in a way that for each trace any variable is assigned at most one time.

The CBMC uses static single assignment, therefore, in this thesis we will restrict exclusively to this form of single assignment. The single assignment form of the program shown in Figure 10 is shown in Figure 13.

The next step is to normalize the program into conditional normal form. After apply it, the transformed code consists only in a sequence of single-branch conditional statements of the form if b then S, where S is an atomic statement. Nested if statements will be transformed in if structures in which the condition of the if is the conjunction of the conditions of the nested ifs. The idea is that the branching structure of the program has now been flattened, so that every atomic statement is guarded by the conjunction of the conditions in the execution path leading to it. An example is shown in Figure 14.

```
max=0;
i=1;
if(i<max_array){
  assert(i>=0)&&(i<max_array);
  assert(max>=0)&&(max<max_array);
  if(a[i]>a[max]) max=i;
  assert!overflow(int,+,i,1);
  i=i+1;
  if(i<max_array){
    assert(i>=0)&&(i<max_array);
    assert(max>=0)&&(max<max_array);
    if(a[i]>a[max])max=i;
    assert!overflow(int,+,i,1);
    i=i+1;
    assert (!(i<max_array));
    }
  }
}
```

⇒

```
max1=0;
i1=1;
if(i1<max_array1){
 assert(i1>=0)&&(i1<max_array);
 assert(max1>=0)&&(max1<max_array1);
 if(a1[i1]>a1[max1])max2=i1;
 max3=(a1[i1]>a1[max1])?max2:max2;
 assert!overflow(int,+,i1,1);
 i2=i1+1;
  if(i2<max_array1){
   assert(i2>=0)&&(i2<max_array1);
   assert(max3>=0)&&(max3<max_array1);
   if(a1[i2]>a1[max3])max4=i2;
   max5=(a1[i2]>a1[max3])?max4:max3;
   assert!overflow(int,+,i2,1);
   i3=i2+1;
   assert(!(i3<max_array1));
  }
 i4=(i2<max_array1)?i3:i2;
 max6=(i2<max_array1)?max5:max3;
}
i5=(i1<max_array1)?i4:i1;
max7=(i1<max_array1)?i4:i1;
```

Figure 13 A static single assignment transformation

3.1.3 *Checking for Property Violation*

After the code had been normalized into conditional normal form, two sets of logical formulas C and P can be extracted. The set of formulas C describes logically the operational contents of the program, and P contains the properties to be checked. The set P is extracted from the guarded assert and assume statements of the normalized code in conditional normal form. The remaining elements constitute the set C. An example shown in Figure 15.

The logical encoding of each *if b then assume* θ statement from the condition normal form is represented by formula $b \rightarrow \theta$. In logical terms, each *(if b then assert* ϕ*)* statement from the normalized condition form is represented by the formula $(\bigwedge A) \wedge \mathrm{b} \rightarrow \phi$, where A is the set of all the formulas assumed before, including the assumptions. Each element of P is negated and individually sent to the SMT-solver with the set C and if it is satisfiable, the example obtain is an violation of element being check.

```
if(True)max1=0;
if(True)i1=1;
if(i1<max_array1)assert(i1>=0)&&(i1<max_array);
if(i1<max_array1)assert(max1>=0)&&(max1<max_array1);
if(i1<max_array1&&a1[i1]>a1[max1])max2=i1;
if(i1<max_array1)max3=(a1[i1]>a1[max1])?max2:max2;
if(i1<max_array1)assert!overflow(int,+,i1,1);
if(i1<max_array1)i2=i1+1;
if(i1<max_array1&&i2<max_array1)assert(i2>=0)&&(i2<max_array1);
if(i1<max_array1&&i2<max_array1)assert(max3>=0)&&(max3<max_array1);
if(i1<max_array1&&i2<max_array1&&a1[i2]>a1[max3])max4=i2;
if(i1<max_array1&&i2<max_array1)max5=(a1[i2]>a1[max3])?max4:max3;
if(i1<max_array1&&i2<max_array1)assert!overflow(int,+,i2,1);
if(i1<max_array1&&i2<max_array1)i3=i2+1;
if(i1<max_array1&&i2<max_array1&&i3<max_array1)assert(false);
if(i1<max_array1)i4=(i2<max_array1)?i3:i2;
if(i1<max_array1)max6=(i2<max_array1)?max5:max3;
if(True)i5=(i1<max_array1)?i4:i1;
if(True)max7=(i1<max_array1)?i4:i1;
```

Figure 14 An normalized code in conditional normal form

```
if (True) assert(φ1);
if (True) x1=y1;
if (True) assume(θ1);
if (True) assert(φ2);
if (True) z1=10;
if (b) x2=x1+y1;
if (b) assert(φ3);
if (!b) z2=x1;
if (!b) assert(φ4);
if (True) x3=b?x2:x1;
if (True) z3=b?z2:z1;
if (True) assert(φ5);
```

$$C = \{x_1{=}y1, z_1{=}10, b \rightarrow x_2{=}x_1{+}y_1, \\ \neg b \rightarrow z_2{=}x_1, x_3{=}b?x_2 : x_1, \\ z_3 = b?z_2 : z_1\}$$

$$P = \{\phi_1, \theta_1 \rightarrow \phi_2, \theta_1 \wedge b \rightarrow \phi_3, \\ \theta_1 \wedge \neg b \rightarrow \phi_4, \theta_1 \rightarrow \phi_5\}$$

Figure 15 Extracted formulas from normalized code in conditional normal form

3.2 Test Data Generation using Bounded Model Checking

Bound model checking of software can be used for test generation. As far as we know, the most relevant work in area was develop by Angeletti et al. [1, 2]. In the following subsections we describe the techniques they present in that two papers.

3.2.1 *Test Data Generation (by Angeletti et al. [2])*

Angeletti et al. present in [2] how to automatically generate tests using CBMC. The key idea is to instrument the code with specific properties so when running the CBMC it will produce counter-examples. The counterexamples produced are tests that allow to achieve a particular criteria coverage.

3.2. Test Data Generation using Bounded Model Checking

The target criteria coverage is decision coverage and authors divide the process in three main steps: code instrumentation, test generation and coverage analysis.

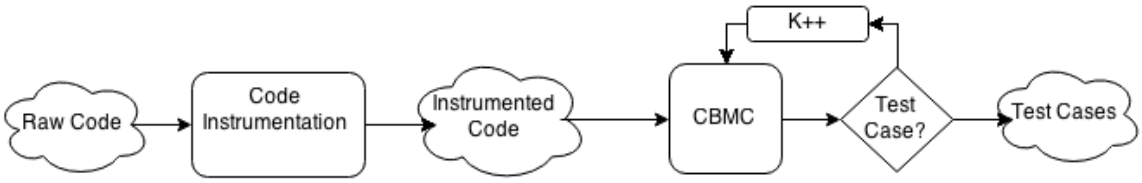

Figure 16 Test coverage generation process.

Code Instrumentation

The code instrumentation step is responsible for instrumenting all the code. In this phase it is establish the locations needed to achieve decision coverage and inserted the necessary statements to generate tests later through the CBMC.

Considering f as the function target in the test generation, the requirements are:

1. The existence of a function *main* invoking f.
2. Each function called by f is completely defined.
3. Model possible user inputs to the f function.
4. Instrument the f function and the ones called by f with necessary asserts to obtain coverage.

The first requirement is due to CBMC to use the main function as a starting point. So for f function to be checked by the CBMC it needs to be invoked by the main function. Also the *main* function body will be used to insert others statements which will allow a correct use of CBMC.

To properly achieve code coverage, all functions depending from the function being coverage also need to be defined. This fact is the reason of the second condition.

For the third point, when a variable is unsigned the compiler attribute the value 0. The CBMC does the same. So it is necessary to model possible user inputs for the input variables from the target function. Model user's input to global variables are also necessary because global variables may affect the functions workflow.

To model possible user inputs the authors used the non-deterministic choice functions from CBMC to achieve it. The f input variables are initialised using the CBMC non-deterministic functions. An important observation for the third item is that authors do not reference the necessity of initialise global variables, although in there examples global variables are initialised in the same way as f argument variables. An example is Figure 17 where input variables(a) and global variables(max, g) are initialised in a non-deterministic way to model possible user inputs.

```
int main (int argc, char * argv [])
    {
  max = NONDET_INT();
  g   = NONDET_INT();
  int a   = NONDET_INT();
  return fut (a);
}
```

Figure 17 Provide non-deterministic input to a function called fut

In the fourth item, instrumentation of f function and the ones called by f, the task is to establish the necessary locations to achieve decision coverage and insert, in that locations, the necessary properties to produce a counterexample by the CBMC. The authors encapsulate the necessary properties with the macro *#ifdef*, each one with different tokens, in order to be able to check later each assertion individually through the CBMC. See the example in Figure 18 where is used as token *Assert*1. If it was not encapsulated they would affect others assertions as explained in Section 3.1.1.

```
#ifdef Assert1
    <properties>
#endif
```

Figure 18 Code exemple of *#ifdef* macro

The less elaborate property that can be constructed to immediately return a counterexample is to check a property that is a contradiction, always false. As presented in Section 3.1.1 such is achieved using *assert* command and is used the property false which in C language translates into the value 0.

A global view of instrumentation transformation of a function is shown in Figure 20.

Test Generation

After code instrumentation the next step is test generation using the CBMC. The instrumented code, from the previews step, is sent to the bounded model checker with the command:

cbmc -D i file-c -unwind k -no-unwinding-assertions

which allows to control the assertion being checked by selecting the corresponding token associated as argument of *-D* option. Other options used are *-no-unwinding-assertions* which disables the unwinding assertion, described in Section 3.1.2, to avoid retrieve violation relative to unwind and the option *-unwind* that allows to choose the unwind bound. The command is run for all assertions. The next step is coverage analysis where it is checked if full coverage was obtained.

The tests are obtained from the counterexample produced from running the CBMC command. A part of CBMC output is shown in Figure 19. From the trace produced for the counterexample, the first attribution to each of the input variables of the functions are extracted.

```
Counterexample:
State 16 file funASSERTIf.c line 47 function main thread 0
------------------------------------------------------------
  max=1 (00000000000000000000000000000001)

State 18 file funASSERTIf.c line 48 function main thread 0
------------------------------------------------------------
  g=0 (00000000000000000000000000000000)

State 23 file funASSERTIf.c line 50 function main thread 0
------------------------------------------------------------
  fut::a=0 (00000000000000000000000000000000)
```

Figure 19 A fragment of a trace form the CBMC command output. The example target $ASSERT\_1$ form the function in Figure 20

Coverage Analysis:

The next step is coverage analysis. In this stage the result obtained from the previous step is evaluated.

If not achieved full coverage, k is incremented and the test generation set is run again until it is obtained full coverage or the maximum value set to k is reached. It is important to observe that when full coverage is not reached all assertion are run again even if it was founded a test at any point. This will increase computational time that could be avoid if the process of incrementation was individually set for each assertion.

The process of checking if full coverage was achieved is realized in two steps. First it is verified if all assertion did obtain a test. If not, the test obtained are sent to external coverage tool for a final decision.

The interaction of all these tree main steps are represented as a diagram in Figure 16.

```
int fut(int a) {
  /*ASSERT_1*/
  int r , i = 0;
  while (i < max) {
    /*ASSERT_2*/
    g++;
    if ( i > 0) {
      /*ASSERT_3*/
      a++;
      if (a!= 0) {
        /*ASSERT_4*/
        r = r + (g+2)/a;
      } else { /*ASSERT_5*/ }
    }
    else {
      /*ASSERT_6*/
      r = r+g+i;
    }
    i++;
  }
  /*ASSERT_7*/
  r = r*2;
  return r;
}
```

⇒

```
int fut(int a) {
  #ifdef ASSERT_1
    assert(0);
  #endif
  int r ,i = 0;
  while (i < max) {
    #ifdef ASSERT_2
    assert(0);
    #endif
    g++;
    if ( i > 0) {
      #ifdef ASSERT_3
      assert(0);
      #endif
      a++;
      if (a!= 0) {
        #ifdef ASSERT_4
        assert(0);
        #endif
        r = r + (g+2)/a;
      } else {
              #ifdef ASSERT_5
              assert(0);
              #endif
      }
    }
    else {
      #ifdef ASSERT_6
      assert(0);
      #endif
      r = r+g+i;
    }
    i++;
  }
  #ifdef ASSERT_7
  assert(0);
  #endif
  r = r*2;
  return r;
}
```

Figure 20 Left side is the function before instrumentation step with comments in the location needed to obtain test *(for the reader best understanding)*. Right side the function after pass the instrumentation step.

3.2.2 *Improving Test Data Generation (by Angeletti et al. [1])*

Following the workflow from the paper [2], which is described in this dissertation in Section 3.2.1, the authors realize the existence of redundant tests in its previous development. So the authors develop a new technique to suppress the creation of redundant tests during the process of coverage test generation, which is presented in [1].

This technique considers the control flow graph to avoid the generation of redundant tests and targets decision coverage. Its key idea is to calculate an independent set of paths and then for each path to generate a test using a bounded model checker, in this case the CBMC. The use of independent set of paths will allow to avoid the creation of redundant tests.

All this steps will be detailed in the following lines. The process is divided in two steps: PathGenerator and ATGbyCBMC.

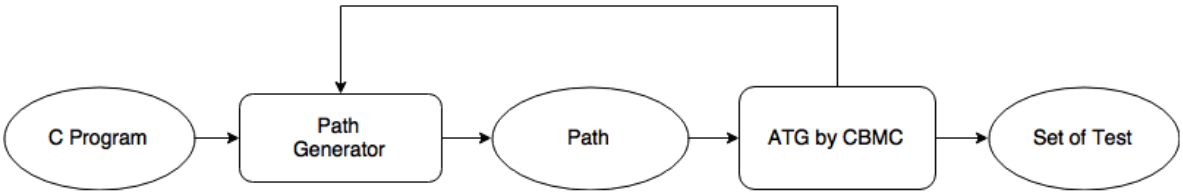

Figure 21 Test coverage generation process.

PathGenerator

The objective of PathGenerator is the construction of independent path set covering the 100% of the branches in the control flow graph. A path is a sequence of branches with its respective code. A set of paths is an *independent path set* if each path in the set contains at least one branch not covered by any other path. After the paths been generated they are sent to ATGbyCBMC produce a test, if possible.

The generation of an independent path set, from all possible paths in a program, is not made at once if we consider the possibility of the existence of infeasible paths. Initially a path is generated. If the path is considered infeasible then a process to determinate the existence of infeasible branch is initialized and any infeasible branch is tagged to be avoid in future path constructions. Otherwise, if the path is feasible, the set of branch that still need coverage is updated . Only then is generated a new path to reach the remaining branches is generated.

The PathGenerator step is not responsible to find out if a path is feasible or not. That responsibility falls over ATGbyCBMC step. The construction of an independent path set is a cyclical relation between this two steps as illustrated in Figure 21. This cycle will run until all branches are coverage or no longer exist more paths to explore.

ATGbyCBMC

The ATGbyCBMC is responsible for receiving a path and generate a test representing that path. The way how the test is created is by using the original program and instrumenting it to produce a new one that imposes that CBMC explores the path received. Only then, after the CBMC have returned (if so) a trace containing the assignments to the input variables, a test is created which runs through the path received.

The way a code is instrumented is complex and hard to explain. Essentially the code is unwound. Then the pieces of code corresponding to the path are collected. The remaining code is removed and the decision commands are replaced by assume annotations containing the property which enforces the corresponding decision for the path. The decision commands, which were removed, contains underlying properties that must be kept in the new program to work properly. So the authors use assume annotations to ensure that properties from the decision commands are kept in the new program.

This transformation results in a program that only contains one path (without any decisions). Due to the complexity of the transformation in the following lines we will use an example to explain step by step this instrumentation process. Consider the piece of code in Figure 22:

```
int func(int a ,int b){

  if (a>2) { a++; }
  else{ a--; }

  if (b<2) { b++; }
  else{ b--; }

  return a+b;
}
```

Figure 22 Peace of code to be use as a example

The first step in the transformation process is unwinding the code considering the bound establish. For the code presented in Figure 22 no changes are need since there are no cycles.

The next step is to instrument the code, by changing it, to take the intended path. The code blocks which would be executed by the decision commands are selected and removed all the others. The code blocks are glued, respecting the path order, using an assume annotation. This annotations are replacing the decisions commands and are necessary to enforce properties inherit from each decision command. The property that is used, in the assume annotation, it is either the one used in decision command or its negation depending on whether the path passes on its true or false branch. Considering that the path received passes in the true branch in first decision and in the false branch in second decision, the blocks that are selected are $a++$ and $b--$ and the decisions properties that must to be ensured are $a > 2$ and $!(b > 2)$ in their respective position. The result is the Figure 23.

```
int func(int a ,int b){

  assume (a>2)
  a++;

  assume (!(b<2))
  b--;

  return a+b;
}
```

Figure 23 Transformed code from Figure 22

It is possible to observe the first ”if” was replaced by the assumption of its condition follow by the code block of the ”true” branch, and the second ”if” was replaced by the assumption of negation of its condition followed by the code block of the ”false” branch.

The ATGbyCBMC is not only responsible for instrumenting the code to be sent to CBMC but also for constructing the test. After instrumenting the code for a path it is necessary to construct a main function that calls the function earlier created and also to insert an assertion that evaluates to false (in the end of the main function) in order to create a test. The main function is not only created for theses two points. As it is described in the previous methodology in Section 3.2.1, the main must model possible user inputs. This process, the main function creation, is the same as described in Section 3.2.1 for the exception of the fourth item. For that reason we will not describe it here.

If it is the case the path crated is feasible, then a test is produced using the trace given by CBMC. Otherwise the process of obtaining the unreachable branches is initialized in other to avoid them in futures paths construction. This task is not described in detail by the authors, but can be easily done by running the CBMC with the annotation $assert(0)$ in the local where we want to check the reachability.

4

OUR APPROACH FOR TEST DATA GENERATION USING CBMC

This chapter is devoted to the description of the techniques and methodologies developed by us and implemented in the tool. Let us first tell how this process took place. Our initial plan consisted in the development of a tool described in the paper [2], which applies the decision coverage criteria, and after it extend the tool to other code coverage criteria. But we ended by developing and implemented three different methodologies, all applying the decision coverage criteria. Such action was driven by the development of new technique to signalize locations for decision coverage.

Following our initial schedule to implement the methodology described in [2], we ended up implementing it but with a subtle derivation because we did not find a freeware tool for coverage analysis. We managed to overcome this problem by changing how the coverage achieved is calculated. Such approach was the first methodology implemented in the tool, which we call *token methodology*.

An issue of the token methodology is that it always generates the same number of tests than the number of locations we want to reach. So after implementing the first methodology we decided to develop a new methodology to overcome this issue.

To develop a new methodology that generates a reduced number of tests, it is required to obtain the locations that have been reached by previous tests. To do so, without the help of any external too, we developed a new technique called the *fresh-variable technique*. This technique associates variables to each location and are then used to force the bounded model checker to generate tests by reference them in assert statements. After a test is generated, we check the value associated to each variable which allows us to know which were the locations reached.

The second methodology developed consists in adapting the algorithmic ideas of the token methodology to *fresh-variable technique*. This new approach allowed us to overcome the issue present in the *token methodology* of generating always the same number of tests than the number of locations reached. We call it the *fresh-variable methodology for single location*.

Both methodologies developed so far have a common issue. The generated set of tests may contain redundant tests. By redundant test we mean that it is possible to remove a test from the set of tests and still reach the same locations. However the removal of redundant tests is NP-complete. It is a problem reducible to the set cover problem [14], and therefore it means that there is no efficient solution.

The third methodology was developed with the intention of reducing to the maximum the number of tests generated and thus also attempt to avoid the generation of redundant tests. This methodology is

also built upon the fresh-variable technique, but instead of targeting a single location, it targets multi-locations, to allow us to have more control in the way we generate the tests. In our implementation each one of this multi-locations are created from combining the locations found in each one of the existing paths in the program. We call it the *fresh-variable methodology for multi-locations*.

Despite the differences between the three methodologies, they have some parts in common. The methodologies are divided in three steps: code instrumentation, test generation and coverage analysis. This chapter begins by describing the different techniques to signalize locations used in code instrumentation and only then presents the details of each methodology.

All the methodologies where developed for the decision coverage criteria, but the same approach can be used to work with different coverage criteria. In Section 4.3 we discuss how the condition coverage and condition/decision coverage criteria can be achieved.

4.1 Signalling Locations

The signalling technique is the process of introducing instructions to force the bounded model checker to generate a test that reaches a certain location. In this work we used two different techniques to signalize locations. The first one originated from the methodology in [2] and it is used in the first methodology. The second one originated from the necessity to overcome some flaws in the first technique and was developed during this dissertation and applied in the second and third methodology.

From this point forward we reference the first technique as the *token technique* and the second technique as the *fresh-variable technique*.

4.1.1 *The Token Technique*

The token technique is well described in Section 3.2.1 in the fourth item of code instrumentation and for that reason we will not enter here in details. This technique inserts in each target location a token associated with the macros $\#ifdef$ and $\#endif$ containing an assert statement. This allows to select a location and to force the bounded model checker to produce a test for it. An example is shown in Figure 24.

```
#ifdef Assert1
    assert(0);
#endif
```

Figure 24 Example of a *#ifdef* macro

The properties inherent to this technique during the test generation are:

- There is no guarantee that the tests generated by the tool will eventually stop its execution.
- It cannot be determined which other locations were achieved during test generation.

- The traces generated by the bounded model checker may not, and most of the times it does not, contains the representation of full path execution.

All these properties derive from the same fact: with this technique the bounded model checker only considers the code execution up to the location we want to achieve. So the trace contains only a part of a full path execution once the reaming part of the path was not evaluated. Therefore, there is no guarantee that the tests generated will eventually stop, once the execution of the code after the assertion may contain cycles that never reach to the stop condition or even multiple recursive function calls in an infinity loop. Also we cannot be determined which other locations were achieved only by reading the trace as only contains a part of a full path execution.

These facts can be overcome if after obtaining the test the locations achieved by running the test would be calculated. Such could be done with coverage tool but would increase the computation time of the all process greatly. So we aim a better solution.

4.1.2 *The Fresh-Variable Technique*

The fresh-variable technique was developed due to the necessity to know which are the locations achieved by each test. It emerged during the development of the first methodology and it uses variables to signalize locations allowing to retrieve all the locations reached during the test generation. The locations reached by a test are obtained by reading the generated trace by the bounded model checker.

Technique description

To apply this technique we associate a new variable to each location and we make a unique assignment to that variable. In Figure 25 we show a small example using the new variables $location\_1$, $location\_2$ e $location\_3$. For each location a different variable must be used. The new variable must be a global and could not exist in the original program. Moreover, they must be initialized with a value different to the value that is assigned to the variables in the locations.

In order to produce a test it is necessary to insert an assert annotation that will evaluate to false. To select the locations we want to target we insert assume annotations, one for each location, before the assert annotation. The proposition used in this assume annotations consists in an equation between the variable associated to the location we want to target and the value that was previously assigned.

This assume annotations are interpreted by the bounded model checker as the value of the variable associated to the location has to be the value assigned in the location when target function finish its execution. As there is no more assignments to this variable besides the one made in the location being target, the bounded model checker will be forced to produce a trace going through that location.

The assert annotation and the assume annotation must be insert in all exit points of the target function or in a more efficient way, immediately after the function call. An example is illustrated in Figure 26 where the target is a single location.

The properties inherent to the fresh-variable technique during the test generation are:

```
int location_1 =0;
int location_2 =0;
int location_3 =0;
...
void maxmin6var(int a, int b, int c, int d, int e, int f){
  location_1 =1;
  int max;
  int min;
  if (a > b && a > c && a > d && a > e && a > f){
    location_2 =1;
    max = a;
        if (b < c && b < d && b < e && b < f){
        location_3 =1;
        min = b;
      }
```

Figure 25 A code fragment of maxmin6var function with variable technique

```
maxmin6var(a,b,c,d,e,f);
assume(location_2 ==1);
assert(0);
```

Figure 26 Piece of code where maxmin6var is called with necessary annotation to generate a test

- There is a guarantee that the tests generated by the tool will eventually stop its execution.
- The traces generated by the bounded model checker contains the representation of full path execution.
- It is possible to determined all the locations achieved during the test case generation.

The execution of every test generated by this methodology eventually halt, because the statement that generates the tests is inserted in the end of the target function. By placing the assert statements at all exit points we force the bounded model checker to consider the full path and reach an exit point. So the test generated will halt and also the trace returned describe all the computation. Therefore we are able to know the locations reached by checking the value of each new variable that was associated to a location.

4.2 METHODOLOGIES

Three different methodologies were developed. The first methodology uses the token technique and the other two uses the fresh-variable technique. They were develop sequentially and comparatively to with each other the second methodology attempts to reduce computational time and resolve redundant tests issue when compared to the first methodology. The third methodology attempts to reduce the number of tests although it may increase the computational time when compared to the second methodology.

4.2.1 *The Token Methodology*

The following methodology was the first one being implemented and is a derivation from the methodology adaptation in [2]. Differences are related to the use of an external coverage tool, because we did not find a suitable freeware tool. So we changed, as little as possible, the methodology to be able to calculate the coverage achieved.

The initial steps are the same as in the paper. Only in the test generation step and in the coverage analysis step changes were made. So in this section we will be only presenting and discussing these changes.

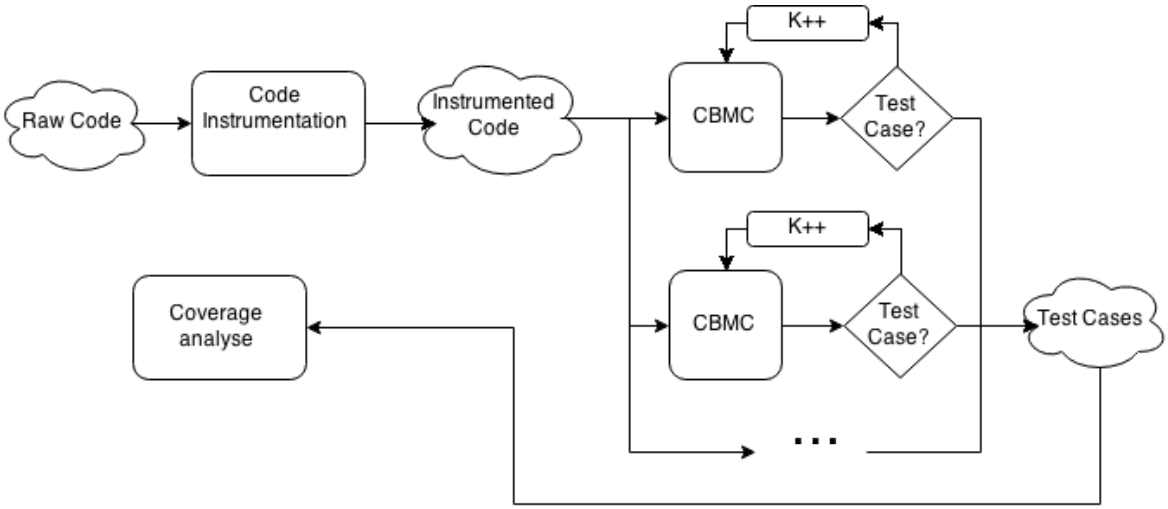

Figure 27 Test case generation following the token methodology

Code Instrumentation

The code instrumentation step is exactly the same as in [2] and was discussed over Section 3.2.1. After the code instrumentation is complete, the code is sent to CBMC to produce the necessary tests.

Test Generation

The test generation step in this methodology is very similar to the original one. In this step the only changes made were in the workflow concerning the CBMC calls and in the bound incrementation.

In the original methodology the CBMC runs for all target locations with the same bound and only then the coverage tool is executed to observe if full coverage is achieved. If it is not the case, the bound is incremented and the process starts again. But in our methodology, each location run individually with its own bound until a trace is generated or the bound reaches its maximum value. This change is due to the process of assessing if full coverage was achieved. In Figure 27 this process is illustrated.

The tests are then created from the traces obtained from CBMC.

Coverage Analysis

The coverage analysis step is devoted to determine the percentage of code coverage achieved. The only accurate information that we have is the minimum number of reached locations by the generated test suite. Each test beyond the target location for which it was generated, it also reaches all the locations that are in its execution trace. However, the token technique does not allow us to obtain this information from the trace produced by the CBMC and we have no external tool to get it. Given these constrains the only information we can give is the minimum percentage of decision coverage achieved during the test generation, which is given by the formula $\frac{Number\ of\ Tests\ Obtained}{Number\ of\ Locations\ To\ Achieve} * 100$

4.2.2 *The Fresh-Variable Methodology for Single Location*

This was the second methodology implemented and puts into practice the fresh-variable technique. It follows the ideas of the first methodology but changes the way how locations are signalized. This will allow to reduce the generation of some redundant tests and possibly also reduce the execution time.

Code Instrumentation

The code instrumentation step follows it very similar to the one used in token methodology. The only differences are that it applies the fresh-variable technique instead of the token technique and, as describe in Section 4.1.2, also declares the global variables that will be used to signal the locations.

Test Generation

After code instrumentation, we have to generate the set of tests that allows to cover all the locations. To do this, we start by selecting one location as a target for the current test generation attempt. The file containing the necessary annotations to generate the test for that location is then produced. This file is then sent to the CBMC and the bound is incremented until the CBMC produces a trace or the maximum bound is reached. When CBMC finds a counter-example, we analyse the output trace and check the locations that have been reached with that trace. With this information, we remove the reached locations from the list of locations yet to be reach. Otherwise, if the CBMC cannot find a counter-example the location is assumed unreachable. The test generation will run again until all locations are reached or assumed unreachable. A pseudo code illustrating this work-flow is shown in Figure 28.

For the sake of readability and modularity, the algorithm uses two auxiliary routines: *select* and *test*. The purpose of the select routine is to select the next location to be targeted. Note that different selection criteria can be implemented and that affects the result produced by the tool with respect to the number of test cases generated and also the execution time of the tool. In the implementation of this function, the heuristic we use was to select the location that is placed deeper in the code structure and

```
Notation:
F = Set of locations which cannot be reached
L = Set of locations still to be reached
N = Number of locations
K = Minimum bound
MAX = Maximum bound
p = A location
ok = Boolean result of finding a test
ls = Set of locations already reached
t = A test
T = Set of generated tests

Algorithm:
N = #L
T = {}
while(L /= {})
{
    p <- select(L)
    (ok,ls,t) <- test(p,K,MAX)
    if (!ok) {
        F <- F U {p}
        L <- L / {p}
    } else {
        L <- L / ls
        T <- T U {t}
    }
}

Percentage of coverage achieved  (1 - (#F/#N)) *100
```

Figure 28 The algorithm relative to the test generation step for the fresh-variable methodology for a single location

also in last part of the program. The test routine is the process of inserting the statements that establish which location to target, calling the bounded model checker and bound incrementation process.

Coverage Analysis

From the test generation results the tests and the locations reached by the tests. To assess the percentage of coverage the formula $\frac{Number\ of\ Locations\ reached}{Number\ of\ Locations\ to\ Achieve} * 100$ is applied. Note that with this methodology we access to all the information needed to calculate the coverage achieved and we do not need a coverage tool.

4.2.3 *The Fresh-Variable Methodology for Multi-Locations*

The idea in the fresh-variable methodology for multi-locations is to consider the paths in order to reduce the number of tests created. It is very similar to the previous methodology but instead of targeting a single location it targets multi-location according to the paths in the program.

We expect that with this approach the number of tests produced can be lower than the ones produced by the previous methodologies, maintaining the coverage level. We are aware that generating multi-location has an additional computational cost that will affect the execution time of the tool. However generating tests without containing redundant tests is an important issue that may well justify the lost of performance.

Compared to what is done in [1], we have an advantage given by fresh-variable technique that enables to search multi-paths with only one call by the CBMC. Although we can not confirm, as we have no access to the tool, we can speculate the computational effort by our methodology is lower.

Code Instrumentation

The code instrumentation is exactly the same as in the previews methodology. The code is instrumented as in [2] changing only the function instrumentation phase where the fresh-variable technique is used as explained before.

Test Generation

The test generation step starts by computing a set of locations sets within the initial bound. This set of locations sets are the multi-locations. From this set of location sets it is selected the one containing the larger number of locations not yet reached. Only then the necessary annotations to reach the locations selected are inserted into the file created in the previous step.

The CBMC will then attempt to generate a trace. If the CBMC is successful, it is updated the list of locations not yet discovered by removing the locations reached by the trace, but also the set of locations sets(which is describe forward in this section). If not, the bound is incremented and a new attempt is made. In the case of CBMC reach the maximal bound without generate a trace, the selected set is removed from the set of sets.

After being attempted to generate a trace for the selected set a new set of locations is selected and the process of attempting to generate a trace starts again until all the location are reached or there is no more sets of locations to search.

The algorithm describing this phase is presented in Figure 29 it contains four auxiliary routines: *test*, *select*, *setOfSetsCreation* and *update*. They were omitted in the sake of readability and modularity. The *test* routine is the process of inserting the statements that establish which locations to target, calling the bounded model checker and the bound incrementation process. The *select* routine purposes is to select the next set of locations to be targeted. Note that the implementation of this routine will influence the results obtained. The heuristic we implemented in the *select* routine chooses the set with more locations not yet reached. The *SetOfSetsCreation* routine represents the generation process of the sets of locations. Note also that the implementation of this routine will affect the tool performance. Our implementation uses paths within the maximal bound to generate those sets. We describe this process bellow. The *update* routine updates the sets of locations according to a set of locations reached. The locations reached are removed from those sets.

```
Notation:
T = Set of tests
L = Set of locations still to be reached
N = Number of locations
C = Set of sets of locations(based on paths)
CFG = Control flow graph
K = Minimum bound
MAX = Maximum bound
p = a set of locations
ok = boolean
ls = set of locations
t = test

Algorithm:
N = #L
T = {}
C <- setOfSetsCreation(CFG,K)
while(C /= {} && L/= {}){
    p <- select(C)
    (ok,ls,t) <- test(p,K,MAX)
    if (!ok) C <- C \ {p}
    else {
        L <- L \ ls
        T <- T U {t}
        C <- update(C,ls)
    }
}
Percentage of coverage achieved (#T/N*100)
```

Figure 29 The algorithm relative to the test generation step for the fresh-variable methodology for a multi-locations

Coverage Analysis

From the test generation results the tests and the locations reached by the tests. To assess the percentage of coverage achieved the formula $\frac{Number\ of\ Locations\ reached}{Number\ of\ Locations\ to\ Achieve} * 100$ is applied. Note that with this methodology we have access to all the information needed to calculate the coverage achieved and we do not need an external coverage tool.

The relation between paths and the sets of locations

The use of paths in test coverage generation is not new. An example is given in [1] paper which is also described in this dissertation in Section 3.2.2. Our methodology can verify multiple paths that passes in a set of locations with only one call to the CBMC, on contrary to what is done in [1]. Comparatively to [1] it is an optimization in the paths search.

The idea is to use the paths as information on the construction of the sets of locations that are feasible, in other words, the sets of locations that could be reach in a single run of the program (a path). Of course we have no guarantee that the sets of locations produced in this process are doable,

because we do not analyse the guards in the decision points. That is the task of the bounded model checker.

By targeting first the sets of locations with higher number of location, we expect to achieve a high level of coverage with a small number of tests and without redundant tests.

In the following lines we describe the advantages in the use of locations sets in this methodology and their construction is described in Section 5.4.

TARGETING MULTIPLE PATHS In the following lines it is explained how it is possible to targeted multiple paths with only one set of locations. We will use a small function for illustrating the process. On Figure 30 left side, we give the example of the bubble sort function and on the right side its control flow graph which relates the blocks of code with the code lines.

```
1  void BubbleSortV(int tab[16]) {
2    int i = 0;
3    int j = 16;
4    int aux = 0;
5    int fini = 0;
6    while (fini == 0) {
7        fini = 1;
8        i = 1;
9        while (i < j) {
10           if (tab[i-1] > tab[i]) {
11               aux = tab[i-1];
12               tab[i-1] = tab[i];
13               tab[i] = aux;
14               fini = 0;
15           }
16           i = i + 1;
17       }
18       j = j - 1;
19   }
20 }
```

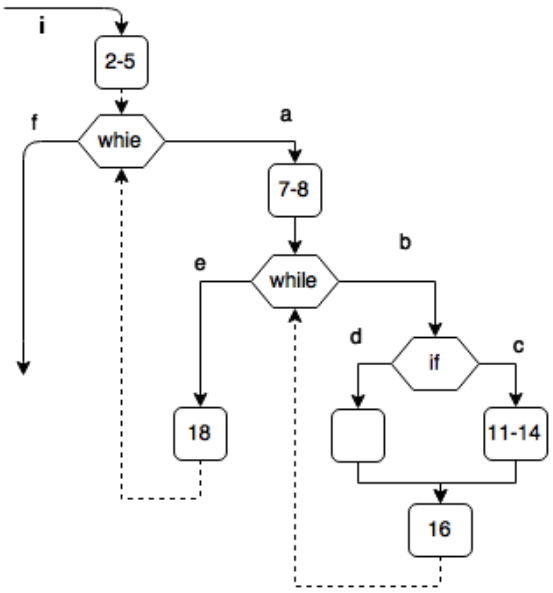

Figure 30 Bubble sort function

Observing the bubble sort function, we can at least enumerate the following paths: the paths [*i,a,b,d,b,c,e,f*], [*i,a,b,c,e,a,b,c,e,f*] [*i,a,b,c,e,a,d,c,e,f*], [*i,a,b,d,e,a,b,c,e,f*]. All this paths can be targeted through the set of locations $\{a,b,c,b,d,e,f,i\}$ because the CBMC will try to generate a trace containing a path that passes in all that locations.

The path selected, contained within the trace, is randomly select from the paths that contain the set of location targeted. Such is not a disadvantage in code coverage generation as our objective is reach all the location and not specific paths.

UPDATING THE SETS OF LOCATIONS After a test has been created the sets of locations are updated. The update removes from each set the locations reached by the test. Doing so, will reduce the car-

dinality of those sets (even making them empty) and simultaneously will increase the probability of being feasible.

To illustrate the process of updating the tests, consider the set of sets of locations as $\{\{f,i\},\{a,e,f,i\}, \{a,b,c,e,f,i\},\{a,b,d,e,f,i\}\}$ and the set of locations reached as $\{a,b,d,e,f,i\}$. The updating removes each location reached from within each set. Moreover, all the resultant empty sets are also removed. In this case the resulting set is $\{\{c\}\}$.

By removing the locations from within a set, we are reducing the properties sent to the CBMC, and therefore, reducing the cost of finding a path.

The resulting empty sets, from removing the locations from within a set, represents the sets which are no longer interesting to target. Their elimination reduce the number of CBMC calls performed by the methodology.

4.3 Extending to Other Code Coverage Criteria

The methodologies we have presented so far were developed for the decison coverage criterion. However it is possible to extend these ideas to other criteria, based on the token technique and on the fresh-variable technique. Here we discuss how test case generation for condition coverage and condition/decision coverage could be done. For each of the criteria we will explain the approach based on the token technique and the approach based on the fresh-variables technique. We will just outline how things could be done. They were not completed finished and they require improvement for sure. Naturally, they are not implemented in the tool.

To extend any of the methodologies describe in this chapter to a new code criteria the only difference is in the instrumentation step. The signalling technique has to be adapted to deal with the corresponding coverage criteria. All the other steps remain the same as explained in the previous sections.

4.3.1 *Condition Coverage*

For condition criterion we have to generate a test suit that each condition in every decision of the program takes all possible outcomes at least once. This matter is well discussed in Section 2.2.3.

From algorithmic point of view, a simple approach is to insert *if* statements to check the one outcome of the condition involved in the decision being test. The *if* statement must be insert in all branch of the decision since we do not know what is the decision outcome.

An sketch of this idea can be found in Figure 31. This simple approach can be use in the construction of booth techniques.

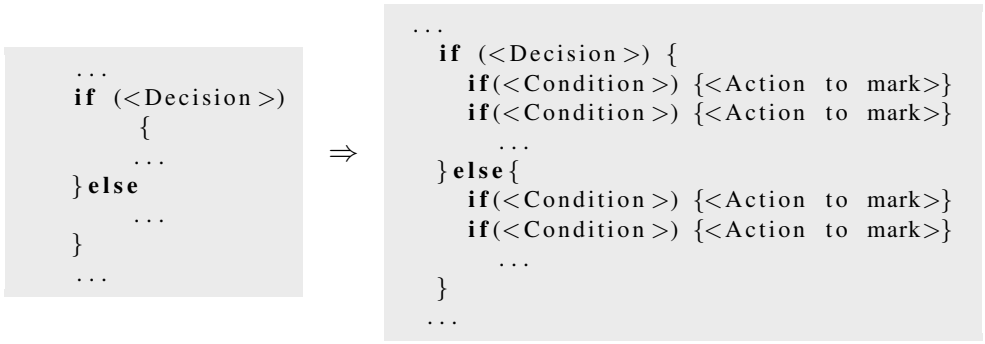

Figure 31 An sketch of idea to check condition in a decision

Token Technique

Following the concepts that characterizes the token techniques, for all the decision points of the program we need to insert a set of $\#ifdef$ macro containing a *if* statement for each condition of the decision targeted. The false assert statement is insert in the body of the *if* statement to trigger the trace creation. An example is shown in Figure 32.

```
if (A || B) {
    #ifdef Assert1
        if(A!=0) {assert(0);}
    #endif
    #ifdef Assert2
        if(A==0) {assert(0);}
    #endif
    #ifdef Assert3
        if(B!=0) {assert(0);}
    #endif
    #ifdef Assert4
        if(B==0) {assert(0);}
    #endif
}else {
    #ifdef Assert1
        if(A!=0) {assert(0);}
    #endif
    #ifdef Assert2
        if(A==0) {assert(0);}
    #endif
    #ifdef Assert3
        if(B!=0) {assert(0);}
    #endif
    #ifdef Assert4
        if(B==0) {assert(0);}
    #endif
}
```

Figure 32 The outcome form the token technique applied to a *if* statement for condition coverage.

Fresh-variable technique

Following the concepts that characterizes the fresh-variable techniques, we need to associate two variables to each condition for all the decision points of the program. One variable to signalling the fact of the condition to be true and the other variable to signalling the condition to be false. Then we insert in each branch of the decision point a set of *if* statements, one for each possible outcome of the condition involved, assigning to the corresponding new variable. As usual the new variables are previously declared as global variables and initialised with the value 0. An example is shown in Figure 33.

```
if (A || B) {
  if(A!=0) {location_1=1;}
  if(A==0) {location_2=1;}
  if(B!=0) {location_3=1;}
  if(B==0) {location_4=1;}
}else {
  if(A!=0) {location_1=1;}
  if(A==0) {location_2=1;}
  if(B!=0) {location_3=1;}
  if(B==0) {location_4=1;}
}
```

Figure 33 The outcome form the fresh-variable technique applied to an *if* command for condition coverage.

Conditions containing commands with side-effects

The existence of commands with side affects with in a condition, such as ++ or - - must be taken in account. By checking a condition that have one of this elements, we change the program state which alters the function behaviour comparatively to the original one. The methods present do not resolve this issue.

A tentative solution to this issue could be to introduce new variables for each condition and immediately before *if* command of the original program assign to those variables the result of the evaluation o the associated condition. Then, in the *if* commands introduced to measure the condition coverage criteria we should use as guards those variables. This way we can guarantee that the conditions are evaluated just once. Yet a problem remains related to the shortcut evaluation of logical connectives. To overcome this problem the assignment to the new variable that keep the result of the evaluation of the conditions has to be done in a way that captures completely the shortcut semantics of the logical connectives in C. This issues needs to be addressed carefully and that is why it has not yet been implemented in the tool.

4.3.2 *Condition/Decision Coverage*

The condition/decision coverage criterion combines both the condition and the decision coverage criteria. To deal with this criteria we can just combine the ideas presented before for those criteria. In Figure 34 and Figure 35 we illustrate the signalling technique that could be used to deal with this criterion based on the token and the fresh-technique respectively. The issues concerning side-effects and shortcuts in condition evaluation are the same as pointed out for condition coverage criterion and the solutions outlined there remain valid.

```
if (A || B) {
  if(A!=0) {location_1=1;}
  if(A==0) {location_2=1;}
  if(B!=0) {location_3=1;}
  if(B==0) {location_4=1;}
  location_5=1;
}else {
  if(A!=0) {location_1=1;}
  if(A==0) {location_2=1;}
  if(B!=0) {location_3=1;}
  if(B==0) {location_4=1;}
  location_6=1;
}
```

Figure 34 The outcome form the fresh-variable technique applied to an *if* command for condition/decision coverage.

```
if (A || B) {

    #ifdef Assert1
        if(A!=0) {assert(0);}
    #endif
    #ifdef Assert2
        if(A==0) {assert(0);}
    #endif
    #ifdef Assert3
        if(B!=0) {assert(0);}
    #endif
    #ifdef Assert4
        if(B==0) {assert(0);}
    #endif
    #ifdef Assert5
        assert(0);
    #endif

}else {
    #ifdef Assert1
        if(A!=0) {assert(0);}
    #endif
    #ifdef Assert2
        if(A==0) {assert(0);}
    #endif
    #ifdef Assert3
        if(B!=0) {assert(0);}
    #endif
    #ifdef Assert4
        if(B==0) {assert(0);}
    #endif
    #ifdef Assert6
        assert(0);
    #endif
}
```

Figure 35 The outcome form the token technique applied to a if command for condition/decision coverage

5

AuTGen-C TOOL

AuTGen-C was the name given to the code coverage tool developed in the context of this thesis. This tool applies the methodologies described in Chapter 4 to programs written in ANSI-C. In this chapter we present *AuTGen-C* as well as the challenges we encountered during its development. In particular, we discuss the design choices, how we have implemented the key topics described in the previous chapters, the challenges founded and the solution for those challenges.

Even before we started the implementation itself, an important decision had to be made. The choice of the programming language to be used in the tool implementation. This choice must contemplate the challenges that may appear. One relevant criterion is that the language chosen offers a parser for the input programs to which we intend to generate tests. if this not the case a parser must be developed from scratch, which might delay the tool development duo to the complexity of the input language.

Depending on the methodology selected, the tool executes differently. The tool is divided in different process, each one with its own task. They are presented in Section 5.1 and debated in the follow section. Also in a tool such as ours is essential to debate and define the concept of unit implemented by us and introduce how can be use the tool we developed in Section 5.6 and Section 5.7 respectively.

5.1 Architecture and Implementation Choices

In this section we focus on the architecture of the tool. We start by discussing the chosen implementation language and the chosen libraries. We finish the section presenting the tool architecture.

5.1.1 *Tools, Language and Libraries*

Haskell was the programming language selected to implement the tool. Haskell[1] is a purely functional programming language with polymorphic and a monadic system. Some of its features include pattern matching, list comprehensions and modularity. Its programming paradigm is ideal for parsing and instrumenting abstract syntax trees which are strong topics in this dissertation. Comparatively to others functional programming languages such as *OCaml*[2] our programming experience using Haskell

1 http://www.haskell.org
2 https://ocaml.org/

was a decisive fact in the selection. Moreover, the language is supported by a big community and a large diversity of libraries, which include libraries for parsing and manipulating C program language.

After choosing the programming language, we had to select libraries to help us develop our tool. First of all, we had to select a parser for C programs. Here, due to the lack of alternatives we have chose *Language.C*[3]. Such a library allows us to parse C programs and to instrument them as described in Section 5.3. Another important library used during the development process was *Text.XML.HXT*[4], which allows us to parse the XML document returned by the bounded model checker.

The CBMC was the chosen bounded model checker. Our choice was influenced by investigation developed in [2] and our experience using it. Moreover, the CBMC is one of the most used bounded model checkers for C code programs and also contains a large diversity of documentation. Initially we started by using CBMC 4.0. However, as CBMC was updated, we also updated our tool to be able to interact with the most recent release of CBMC. Currently we are supporting CBMC 5.0 which includes many improvements relatively to the initial version.

The operating system used during development was Ubuntu 12.04 LTS running on 1.8Ghz dual core processor machine with 4GB of RAM memory.

5.1.2 *Architecture and Source Code Structure*

Let us now describe how the tool is implemented. The tool architecture is composed by different components. All methodologies have in common the pre-instrumentation and test vector extraction as is shown in Figure 36. In the figure it is also possible to observe that the coverage analysis is also the same for all methodologies.

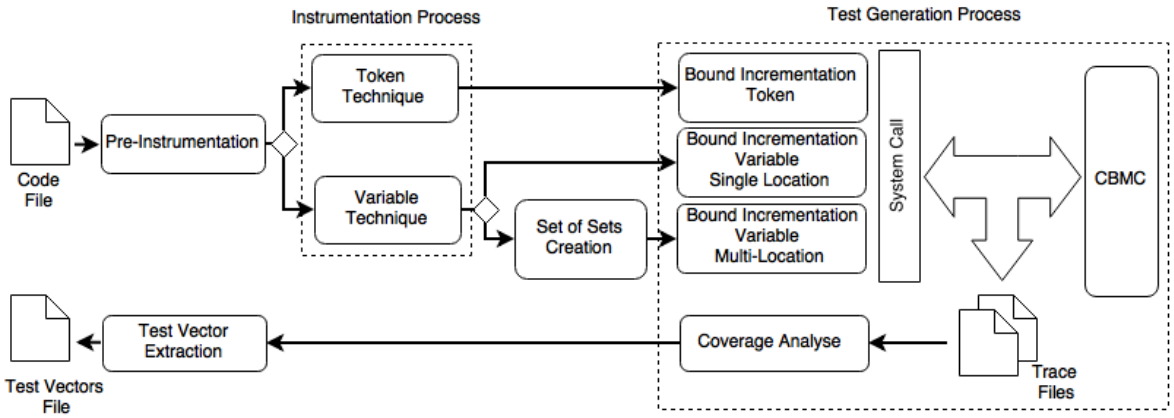

Figure 36 Tool architecture

3 https://hackage.haskell.org/package/language-c
4 http://hackage.haskell.org/package/hxt

The organisation of the code is shown in Figure 37. The main function is declared in the *Main.hs* file and starts by interpreting the input options followed by the test generation itself.

Apart from the *Main.hs*, the main directory also contains *Opts.hs*, *Automation.hs* and *Configurations.hs* files and some directories. All these files contains auxiliary functions which are called by the *Main.hs* file. The *Opts.hs* file contains all the subroutines responsible for interpreting the input options. The *Configurations.hs* contains the parametrizable values accessed over the several phases. Finally, the *Automation.hs* file contains the auxiliary function that initializes test generation itself.

The code instrumentation is the first process executed by the tool. This step is divided in the pre-instrumentation process and the signalling technique application process.

All the functions related to the pre-instrumentation are in *PreImplementation* directory. This directory contains the automation process responsible for the non-deterministic attributions, variable declarations and initialization, function declaration and for extracting information from the code that will be used in the following steps.

Depending on which methodology is being applied, one of the two signalling techniques is used. All the functions related to the application of one of this techniques are in *Instrumentation* directory. The *Instrumentation/Coverage/StatementDecisionCoverageToken.hs*, is related to the token technique and the *Instrumentation/Coverage/StatementDecisionCoverage.hs* to the fresh-variable technique. Both are called by *Instrumentation/Automation.hs* that contains automations responsible for applying the coverage.

After the locations are marked in the code the test generation procedure follows. In the case of fresh variable methodology for multi-locations the sets of locations are created, and only then the test generation procedure starts. All the functions related to the sets of locations generation are in the *PathSet* directory.

The test generation procedure includes the process of storing the generated tests, establish which still need to be reached, manage the bound incrementation and calling the CBMC. All function related to this procedure are in the the *TestGeneration* directory and each methodology have its own automation. The *TestGeneration/Token/Automation1.hs* file contains the function for the automation related to the token methodology. The *TestGeneration/Variables/Automation2.hs* and *TestGeneration/Variables/Automation3.hs* files contain the function for the automation related to the variable methodology. It is also during this process that the necessary information for calculating the level of coverage is obtained.

Upon the conclusion of test generation procedure, the traces produced still need to be transformed into test vectors. The functions responsible for transforming the traces in to test vectors are in the *TestGeneration/TraceParse.hs* and *XML/XmlCBMC.hs* files.

Two other directories, not yet referred, are the *Pretty* and *Types*. They contains function related to types transformation and types declarations required by other components.

AuTGen-C Files

- Main.hs
- Opt.hs
- Automation.hs
- Configurations.hs
- **Instrumentation/**
  - Automation.hs
  - **Coverage/**
    - StatementDecisionCoverage.hs
    - StatementDecisionCoverageToken.hs
- **PathSet/**
  - Convert.hs
  - PathSetCreation.hs
- **PreInstrumentation/**
  - Automation.hs
  - ExternalFunctionDeclaration.hs
  - FunctionDependencies.hs
  - FunctionVars.hs
  - GlobalVars.hs
  - StatementsAssiments.hs
  - StatementsDeclarations.hs
  - Statements.hs
  - StatementsUtill.hs
  - Util.hs
  - **Variables/**
    - LocationVars.hs
- **Pretty/**
  - Pretty.hs
  - Test.hs
- **Types/**
  - Annotations.hs
  - AST.hs
  - CGF.hs
  - EqUtil.hs
  - Option.hs
  - Paths.hs
- **TestGeneration/**
  - TraceParse.hs
  - **Token/**
    - Automation1.hs
  - **Variables/**
    - Automation2.hs
    - Automation3.hs
    - Statements.hs
    - Test.hs
- **XML/**
  - XmlCBMC.hs

Figure 37 Structure of the tool filesystem

5.2 Pre-Instrumentation

The first process shown in the tool architecture(Figure 36) is the pre-instrumentation. However, for this process to be possible the tool has first to perform some standard tasks, such as, for instance, parse the input program and interpret the user input options (command line flags). We omit a description about these implementation details because they are standard tasks performed by any regular tool. Nonetheless, it is important to note that after these tasks are performed one obtains an AST with the input program and another structure with the selected options.

One of options that the user has to specify is the name of the target function (as well as the file name) to be used as entry point for the generated tests. The arguments of this function must be modelled in a way that the test vectors generated contains possible user inputs, as explained in Section 3.2.1.

The principal idea of the pre-instrumentation is exactly to model the arguments of the target function. A new main function is created whose purpose is to call the target function with the modelled arguments. For each argument, we analyse its type and assign to it an arbitrary value. In CBMC this can be done by assigning to a certain variable the result of an external function whose return type matches the variable type. Predefined external functions exist in CBMC (such as the `int nondet_int();`) and those do not have to be declared. If the assignment `x = nondet_int();` takes place, CBMC will consider that `x` has an arbitrary value. As an example see how variable `show_help` is assigned in Figure 38.

If a predefined external function is not provided by CBMC, it can just be declared. This is particeularly useful for user defined structures. Figure 38 shows the declaration of an external function that returns a `struct stat`. This function is then used to assign an arbitrary value to variable `out_stat`.

```
extern struct stat nondet_structstat();

int main() {
    int show_help;
    struct stat out_stat;
    out_stat = nondet_structstat();
    show_help = nondet_int();
...
```

Figure 38 Part of program emphasizing non-deterministic initialization

LIMITATION IN THE METHOD The method described previously has some limitations due to the way CBMC presents counter-examples. For variables declared as pointers, CBMC only shows the address of that pointer and not the content in that address. Certainly a content value was taken into account during the model checking process which might have been crucial for detecting the counter-example generated. Unfortunately, CBMC does not shows it in the returned counter-example. Consider the example in Figure 39. If CBMC returns a counter-example the value of `*aux` will not be visible.

```
int f(int *x){
  ...
}

extern int * nondet_int_pointer();

int main(){
  int *arg = nondet_int_pointer();
  f(arg);
}
```

Figure 39 Part of program emphasizing an alternative initialization method

We try to resolve this issue using auxiliary variables. For the example in Figure 39, we would declare a new variable `int aux = *arg;` to capture the value `*arg` as shown in Figure 40.

```
int f(int *x){
  ...
}

extern int * nondet_int_pointer();

int main(){
  int *arg = nondet_int_pointer();
  int aux = *arg;
  f(arg);
}
```

Figure 40 Part of program emphasizing an alternative initialization method

This alternative initialisation method would result if pointer only pointed to “simple” types, such as int and char. A “complex type” is for example arrays. A variable of the type `int*` may point to a array of type `int`. For the example in Figure 40 if the function expected an array only the first position of the array would be recovered.

Once this alternative initialization method, for some cases, only retrieves part of the crucial information necessary to create a test, the test created may not be lead to the program execution as intended. Moreover, the tests created will probably introduce redundancy and reduce the percentage of coverage achieved.

In attempt of retrieve the full information was try auxiliary variables of array type with fixed size, once the CBMC can show correctly the values in arrays with fixed size. The example in Figure 41 is shown the `aux` variable as an array of size 3. Even with this change we continue with same issue. The size use in the auxiliary array variable is not enough to retrieve the position 6, which is a crucial for the test generation. This solution to work requires to know the correct size to be use in the `aux` variable.

```
int f(int *x){
  if (x[6]>3)
    ...
}

extern int * nondet_int_pointer();

int main(){
  int *arg = nondet_int_pointer();
  int aux[3] = *arg;
  f(arg);
}
```

Figure 41 Part of program emphasizing an alternative initialization method

As solution was not found, none of this alternatives was implemented. Also research over this topic lead us to the information that pointer allocation and other related features are under development by CBMC developers and is expected news over this topics in the next CBMC releases.

5.3 Instrumentation Process for Decision Coverage

Before the test generation process, the target code is instrumented for the decision criterion. The notion of decision coverage in our tool is as follows: every decision in the program has taken all possible outcomes at least once and every point of entry has been invoked at least once (note that some authors defend a stronger criterion as discussed in Section 2.2.2, every point of exit must also be invoked at least once). During this process the locations are identified and the annotations are inserted with the corresponding signalling technique to the methodology in use. The instrumentation process

starts by receiving an abstract syntax tree generated by pre-instrumented process as explained in the previous section.

The tool has first to calculate function dependencies, according the user choice. For that, we iterate over the abstract syntax tree and for each function call and we keep track of its dependencies.

The abstract syntax tree generated by the *Language.C* library does not consider directives. We only can speculate that the reason of such a behaviour is related to the process used by the library. It starts by invoking an external C preprocessor, which removes all directives, and only then parses the resulting program.

In order to instrument the code using the token methodology we had to develop a solution to support the *#ifdef* directive. Two possible solutions emerged. The first option was to change the abstracted syntax tree data type and create the element corresponding to directive *#ifdef*.

The other option, that we ended up using, consisted in using a functionality given by the library. The abstract syntax tree structure is created in such a way that every element in it can carry an auxiliary parameter. The only restriction is that all auxiliary parameters must have the same type.

For both alternatives, the pretty printer component from the *Language.C* library would have to be modified. Nevertheless, if the first option would have been used, we would also have to be changed the structure provided by the library. Besides that using the second option facilitated the development of other tasks.

The Data Supporting the Annotations

The data supporting the annotations is defined in Figure 42. The type shown contains the elements related to the annotations used to apply both signalling techniques.

```
data Annotation =
    IFDef Int [Annotation]
  | Assume Expression
  | Assert Expression
  | Label Int
```

Figure 42 Annotation type definition

An *Annotation* instance can be created by using one of four constructors. The *#ifdef* directive can be created by the *IFDef* constructor. Its parameters are an identifier (*Int*) to the location in question and a list of annotations (*[Annotation]*). The list of Annotation correspond to the annotations to be inserted in the *#ifdef* body. The standard annotations from bounded model checkers, *assume* and *assert* statements, can be created by the *Assume* and the *Assert* constructors. Both have as parameter a C language expression (*Expression*). The *Label* annotation is used by fresh-variables methodologies and represents the attribution to the variable associated to that location. Its contains a parameter (*Int*) that is the identifier of the location. It is used to create the assignmentused in the fresh-variable technique.

The introduction of annotations in the abstract syntax tree

The process of inserting the required annotation for both signalling techniques only differ in the annotations that are inserted. This process starts by receiving the abstract syntax tree from the pre-instrumentation process and then changes its auxiliary parameters to receive the annotations. It is also applied some simplifications, for instance *do while* loops are transformed into *while* loops, required by both signalling techniques.

```
type AuxiliaryParameter = ([Annotation],[Annotation])
```

Figure 43 The auxiliary variable type definition

The auxiliary parameters type used is shown in Figure 43. The *AuxiliaryParameter* contains two fields, each one containing a list of *Annotation*. This two fields divide the annotations that must be inserted in true and false outcome of a condition statement. The type used in the fields may be considered excessive because there exists simple types to represent the auxiliary parameter. Nonetheless, we aimed to keep it as general as possible thinking already in the instrumentation for other coverage criteria. For the fields that do not contain any annotation is used the empty list.

The *AuxiliaryParameter* instances which receive annotations are the ones which are appended to statements related to decisions, for instance *if* and *while* statements. Depending on the signalling technique being used is inserted the different annotations. For the token technique it is inserted the *IFDef* annotation with a assert statement with the false expression (*IFDef i [Assert 0]*). For the fresh-variable technique it is inserted the annotation correspondent to the variable assignment (Label i). In both cases the *i* element is the location identifier.

The pretty print

When the abstracted syntax tree is pretty printed, the elements from the *Annotation* type must be also printed. Each *Annotation* element is printed as shown in Figure 44. The *e* and *i* are the arguments used in there construction. Also it is use the name `DEFINE_` as the macro's name in the *#IFDef* and the name `cc_loc_` as variables name in the variables *Label*.

```
cc_loc_i = 1;
```

(a) *Label*

```
assert(e);
```

(b) *Assert*

```
__CPROVER_assume(e);
```

(c) *Assume*

```
#ifdef DEFINE_i
 /*Annotations
     prettyprint*/
#endif
```

(d) *IFDef*

Figure 44 Annotations pretty print

```
switch (i)
{
case 1:
cc_loc_2 =1;
case 2:
cc_loc_3 =1;
    i = 0;
default:
cc_loc_4 =1;
}
```

```
if (i>0)
{
cc_loc_5 =1;
    i++;
}
else
{
cc_loc_6 =1;
    i--;
}
```

```
while (i < 0)
{
cc_loc_5 =1;
  i++;
}
cc_loc_6 =1;
```

Figure 45 Statements pretty print

The annotations inserted in the auxiliary parameters are placed in beginning of the corresponding sequence of statements. In Figure 45 is shown on the left had side the example of pretty printing an switch statement, on the middle the pretty printing of an if statement and on the right the pretty printing of a while loop.

5.4 Set of Locations Sets Generation

The set of sets generation is a process that only occurs when the fresh-variable methodology is used for multi-locations. After the code is instrumented accordingly to the previous section, the resulting abstract syntax tree is used to generate possible execution paths that are transformed in set of sets to be used by the fresh-variable methodology for multi-locations.

Since the bounded model checking only checks executions within the established bound, only execution paths within the establish bound are considered in the construction of the set of sets. The generation of sets from execution paths outside of the established bound would be a waste of computational time as the bounded model checker cannot generate traces containing those paths.

The process of creating the set of locations starts by creating a new data structure that captures exclusively the control flow of the initial program. Such a data structure is shown in Figure 46 and is used to agile the set construction process. Note that at this point we know that our target program is syntactically well constructed.

The *ReducedTree a* data type show in Figure 46 is the new data structure used to capture the control flow of the initial program. For each function in the initial program a *ReducedTree* is constructed. The *ReducedTree a* is a list of elements of data type *Command a*, which corresponds to a sequence of statements from a function in the initial program.

The *Command* data type can be created using different constructors. The constructor *C* is used when a function call is met. The constructor *R*, *B* and *Cont* is used whenever a return, break, or continue statement is encountered respectively. When an assignment inserted by the instrumentation process in the fresh-variable technique is met, the *Id* constructor is used. For switch statements we use the *Switch* constructor and for each case we use the *Case* constructor. Finally for the if, and

```
data ReducedTree a = [Command a]
data Command a =
     C name
   | R
   | B
   | Cont
   | Id a
   | Switch [Command a]
   | Case [Command a]
   | If ([Command a],[Command a])
   | Loop ([Command a],[Command a])
```

Figure 46 The commands in the reduced abstract syntax tree

while statement, the *If* and *Loop* constructors are respectively used. Note that the *Switch* and *Case* constructors have also one argument used to capture their content. The same applies to the *If* and *Loop*, but in these cases, both have two arguments: one for the case in which the condition is true and another for the case in which the condition is false.

```
/*  The cc_loc_* are the
    variables signalizing the
    locations  */
      int trap(int a){
        cc_loc_1 =1;
        while (a < 6)
        {
          cc_loc_2 =1;
          if (a % 2){
            cc_loc_3 =1;
            a++;
          } else {
            cc_loc_4 =1;
            a = a + 2;
          }
        }
        cc_loc_5 =1;
        return a;
      }
```

Figure 47 The trap function instrumented using the fresh-variable technique

An example of a *ReducedTree* instance corresponding to the code shown in Figure 47 is `[Id 1,Loop ([Id 5],[Id 2,If ([Id 3],[Id 4])]),R]`. Note that the assignments represented in the program as `a++` and `a = a + 2` are not captured in this new representation, but the special assignments (which in reality are just auxiliary parameters in the AST) are captured.

To transform a *ReducedTree* into to set of locations sets, for each instance of the *ReducedTree*. From there, the process goes backwards until the first element in the list. To evaluate the last element, an empty set is received corresponding to the possible execution paths from that point onwards. The

result of evaluating the last element is propagated to the evaluation of the previous. The process follows like this until the first element.

Note also that some instances of the *ReducedTree* can have arguments. Those will originate different set of locations. For instance, the evaluation of an the command `If ([Id 1],[Id 2])` will result in the following set: `{{1},{2}}`. If instead we have another location before the if, such as `[Id 3, If ([Id 1],[Id 2])]` the result of the If command will be propagated backwards, resulting in the following set: `{{3,1},{3,2}}`.

A special case of this evaluation is the Loop constructor. In this case, one must consider the result of multiple iterations. For that we start by creating a set of locations corresponding to the loop body, and after that we apply the cartesian product as many times as the chosen bounded (this is the same value given to the BMC tool).

Other constructors with special semantics is the *R*, *B* and *Cont*. Note that the *R* constructors corresponds to the return statement. That means that whenever an *R* instance appears the execution of that function must stop, and therefore all subsequent executions paths must be ignored. The *B* constructor represents the break statement and therefore, the subsequent commands in the same scope must be ignore, making the execution continue in the next scope. Finally the *Cont* constructor, corresponding to the continue statement has only to ignore the subsequent commands in the current execution. Note that these constructors must be evaluated first, in order to capture the described behaviour.

Another command requires special attention is the *goto* statement. This command is not supported in the current version of the tool. Such could be implemented by having a set of locations associated to each label. This way, each time a `goto label_1;` is found we combine the current set with the set associated to the `label_1`.

The set of locations obtained from this procedure are then used by the fresh-variable methodology for multi-locations as explained in Section 4.2.3.

5.5 Test Generation and Test Vector Extraction Processes

As explained previously, for the generation of set of tests we use CBMC. In this section we describe how to interact with CBMC to perform bounded model checking of software to the instrumented file. Moreover, we also describe how to interpret the results given by CBMC to create a set of tests.

5.5.1 *CBMC Interaction and Test Construction*

The interaction between our tool and the CBMC tool is done through system calls. Every time the tool needs to perform bounded model checking to an instrumented program and produce a test case we print the program to a file and invoke CBMC through a system call. The CBMC outputs the result to the standard output which is then interpreted by our tool.

The performed system call has the following format: *cbmc -D <macro> <file-name> --unwind <number> --no-unwinding-assertions --xml-ui*, where the option *-D <macro>* is only used when the token methodology is being used (more details are given in Section 3.2.1). The option *--xml-ui* is used for CBMC to use a XML file as output. Such facilitates the interpretation of results and creation of tests.

We use the *Text.XML.HXT* library to parse the CBMC output file. Such a file includes a trace that leads to an assertion violation. In our case, such a trace, represents exactly an execution going through the locations we specified. In simplified terms, a trace corresponds to the evolution of the variables along the execution of the program. Figure 48 shows part of a trace. In particular it shows the result of an assignment to variable `cc_loc_3` (an auxiliar variable introduced in the pre-instrumentation process). From the XML element it is possible to extract different information, such as, for instance, the type of the variable, the file and the line in which it appears, and the value that is assigned to the variable.

```
<assignment assignment_type="state" base_name="cc_loc_3"
  display_name="cc_loc_3" hidden="false" identifier="cc_loc_3" mode="C"
  step_nr="72" thread="0">
    <location file="InstrumentedCode.c" function="f" line="15"/>
    <type>int</type>
    <full_lhs>cc_loc_3</full_lhs>
    <full_lhs_value>1</full_lhs_value>
    <value>1</value>
    <value_expression>
      <integer binary="00000000000000000000000000000001" c_type="int"
          width="32">1</integer>
    </value_expression>
</assignment>
```

Figure 48 *XML* assignment

The require information to be extracted, from each trace, may change depending on the methodology in use. Something that is common to all techniques is the initial values of the function input arguments. Those are going to be used in the generated test. Moreover, it is important to extract the locations that were reached with the current execution. All this information is easily accessible in the XML file. It consists mainly in reading the carry by the variables. The reached locations are identified by observing whether the variable associated to a location was attributed or not. The values attributed to the arguments of the target function are obtained by filtering all the attributions in the main function and the selecting the ones used to call the target function.

The reached locations are identified by observing whether the variable associated to a location was attributed or not. The values attributed to the arguments of the target function are obtained by filtering all the attributions in the main function and the selecting the ones used to call the target function.

With the information extracted from the traces produced by CBMC we produce the set of tests which are then stored in a file. Figure 49 shows an example of such a file. Each line represents a test

input case, and within each line we have the values that are assigned to each variable. More concretely each line is composed by the argument type, name and the value it takes on that test.

```
1 int i  257702809, int j          0, int k  -257702802;
2 int i -634666905, int j 1281384480, int k  1254105088;
3 int i -760495001, int j -760495001, int k -1901164487;
4 int i  671420665, int j  134545163, int k   671420665;
5 int i  761215897, int j -1387703479, int k -1387703479;
6 int i 1512386809, int j 1512386809, int k  1512386809;
7 int i -770980761, int j -2025477607, int k -1531138496;
8 int i -729562009, int j 1077944352, int k  1077944352;
```

Figure 49 Test vectors file

5.5.2 *CBMC Limitations*

When using CBMC as an auxiliary tool for generating tests, we are fronted with some limitations. In our point of view, the tool should allow for the user to verify only the inserted properties. Unfortunately this is not possible and CBMC always inserts some properties to be later verified. This behavior can lead to the generation of counter-example traces that are not related to test generation process, but else to the violation of CBMC inserted assertions.

An alternative we had to consider in order to avoid the properties inserted by CBMC was to use the command line flag `--property N`. The behavior of this flag is that CBMC will only take verify the property number `N`. Note that a value is assigned to each property by CBMC, and therefore, we must make sure that we are checking the correct property.

The value associated by CBMC to the assert responsible to trigger the trace generation when use the fresh-variable technique is always the same. However, this behaviour, by the CBMC, is not observed when use the token technique.

5.6 The Unit Used

To allow the tool to adapt to the criterion that an user may have as unit, we developed three criteria from which the user may choose. The first one will cover the target function and all the function that may be executed from the target function. The second criterion only covers the target function. And the third criterion covers the target function and the functions indicated by the user. This three alternatives were named as dependency unit, single unit and selected unit respectively.

Consider the example, shown in Figure 50, where the function A calls the functions B and C, and the function C calls D. If the function a was selected as target function, for the first alternative the locations from A, B, C and D would be taken in consideration. For the second alternative only the

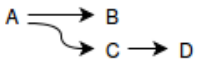

Figure 50 The function dependencies

function *A* would be consider and for the third alternative *A* and the ones indicated by the user would be consider.

5.7 TOOL GUIDE

In this section we present a tutorial about the tool usage. We cover different ways of invoking the tool, by showing the command flags that must be provided to it. Moreover, we show how to use different methodologies and different units.

A SIMPLE CALL

AuTGen-C -t <function-name> <file-name>

This is the simplest way of invoking the tool. The option *-t* follow by the function name is used to indicate the target function. By default, this command will apply the fresh-variable methodology for single location with a initial bound of one and a maximum bound of five. The unit us by default is the dependency unit.

ESTABLISH THE INITIAL AND MAXIMUM BOUND

AuTGen-C -t <function-name> <file-name> -s <number> -m<number>

The command line flags -s and -m can be used to indicate respectively the minimum and maximum bound.

THE UNIT TYPE SELECTION

AuTGen-C -t <function-name> <file-name> --uDepend
AuTGen-C -t <function-name> <file-name> --uSingle
AuTGen-C -t <function-name> <file-name> --uSelect -f<function-name>

To select the kind of unit the user is interested to cover, the command line flags --uDepend, --uSingle and --uSelect can be used. When the first is used, the dependency unit is used. When the second is used, the single unit is used and finally, when the last is used the user can provide the functions to be covered as parameters through the flag $--f$, one for each function the user wants to add.

THE METHODOLOGY SELECTION

AuTGen-C -t <function-name> <file-name> --decision token
AuTGen-C -t <function-name> <file-name> --decision single
AuTGen-C -t <function-name> <file-name> --decision multi

To select the methodology to be used, the *--decision* command flag can be used, together with a parameter: *token* for the token methodology; *single* for the fresh-variable methodology with single location; *multi* for the fresh-variable methodology with multi location.

OTHER OPTIONS

AuTGen-C -t <function-name> <file-name> -v
AuTGen-C -t <function-name> <file-name> -h

Finally, as usual, the command line flags *-v* and *-h* can be used to show respectively the version of the tool and some helpful information.

6

EVALUATION AND CONCLUSIONS

In this section we evaluate our tool, and provide an overview of its capabilities. Moreover, we perform an empirical study comparing the different methodologies using different case studies. We start by presenting the results obtained by running our tool, using different methodologies, with different algorithms and then we make a global analysis of the tool. We finish this chapter and this dissertation with some conclusions and some ideas for future work.

6.1 TOOL EVALUATION

The first two case studies were previously used to validate *LocFaults* tool [4] and are available from `http://www.i3s.unice.fr/~bekkouch/Benchs_Mohammed.html`. The first case study is a C implementation of the famous bubble sort ordering algorithm and the second, which we will call maxmin6, is an implementation of an algorithm that calculates the maximum and the minimum value of six variables.

The third case study, called cars, was previously used as a benchmark in [10] and is available from `https://bitbucket.org/vhaslab/benchmarks/src/4978b4b15bb2/dagger/ORIGINAL/`. Finally the last case study we consider is the grep utility version 2.21 from unix system, whose source code is available from `ftp://ftp.gnu.org/gnu/grep/`.

Each one of this case studies was selected because they contribute to different aspects of the evaluation. The bubble sort function contains two nested loops, the maxmin6var function contains no loops, the cars function contains non-deterministic functions that determines the outcome of decisions and the grep utility is a large real world application (contains more than 2000 lines of code) and therefore allows us to observe how the tool scales.

For each case study, we run our tool multiple times changing only the lower and upper bound. Moreover, for each bound interval, we run it with the different methodologies. The tables containing the results are divided into groups and each group contains the different methodologies with the same bound interval and unit used.

With respect to the columns, we present the following information:

- *Methodology:* the methodology in use;

- *Computation Time / CPU Time:* total time, and time omitting the CBMC computation time;
- *Number of locations to reach:* total number of locations;
- *Code coverage:* percentage of code that has been reached;
- *Number of tests:* number of generated tests;
- *Missed locations:* the locations that were not reached by any test;
- *Infeasible set of locations:* number of set of locations that have been generated and tried but were infeasible.

Bubble Sort

		BubbleSort					
Bound range	Methodology	Computation Time / CPU Time	Number of locations to reach	Percentage of coverage reached	Number of tests	Missed locations	Infeasible set of locations searched
[min:1 max:1]	Token	2s / 0.54s	7	71%	5	[2,4]	
	Fresh-Variable Single location	2s / 0.03s	7	0%	0	all	
	Fresh-Variable Multi-location	1s / 0.02s	7	0%	0	all	4
[min:9 max:9]	Token	4s / 0.70s	7	71%	5	[2,4]	
	Fresh-Variable Single location	3s / 0.14s	7	0%	0	all	
	Fresh-Variable Multi-location	1s / 0.09s	7	0%	0	all	5
[min:16 max:16]	Token	6s / 2.18s	7	100%	7	none	
	Fresh-Variable Single location	2s / 1.12s	7	100%	1	none	
	Fresh-Variable Multi-locations	2s / 1.23s	7	100%	1	none	0
[min:1 max:16]	Token	14s / 2.48s	7	100%	7	none	
	Fresh-Variable Single location	7s / 1.38s	7	100%	1	none	
	Fresh-Variable Multi-locations	7s / 1.47s	7	100%	1	none	0

Table 1 The bubble sort evaluation results

This case study consists of a bubble sort algorithm implemented for arrays with 16 elements. Note that for a lower and upper bound of one the token methodology is already able to reach 71% of decision coverage, failed only to coverage two tests. However, for the other methodologies, tests are not generated.

When we set the upper bound to 16, all methodologies are able to generate tests which reach 100% of decision coverage. Nonetheless in this case, we can observe that when using the methodologies

based on the fresh-variable technique only one test is generated and the token methodology generates seven tests. Taken in account the case study, we can affirm that six of seven tests generate by token methodology are redundant.

With respect to the execution time, the token methodology is always slower. It is with initial and maximum bound of sixteen that the disparity in execution time of the methodologies is greater. We can also observe a scale in execution time when used the initial bound of one and max bound of sixteen comparatively to the use of initial and maximum bound of sixteen.

With respect to the execution time, the token methodology is always slower. Note in particular the high values in the case in which the lower bound is 1 and the upper bound is 16. This will make that our tool will first try to cover all locations with a bound 1 when calling CBMC, and then if some location is still not reach with the produced tests, it will increase the bound until all locations are reached or it reaches the bound 16. This case studies requires a minimum bound of 16 to cover all locations, therefore, it is more efficient if one starts to consider the minimum bound of 16.

Maximum and minimum of six variables

		Maxmin6var					
Bound range	Methodology	Computation Time / CPU Time	Number of locations to reach	Percentage of coverage reached	Number of tests	Missed locations	Infeasible set of locations searched
[min:1 max:1]	Token	16s / 2.12s	59	100%	59	none	
	Fresh-Variable Single location	12s / 2.68s	59	100%	30	none	
	Fresh-Variable Multi-location	12s / 2.68	59	100%	30	none	0

Table 2 The maxmin6var evaluation results

As expected, since this case is absent from loops, all three methodologies reached 100% of code coverage only with lower and upper bound of one. The token methodology generates fifty nine tests and the methodologies based on the fresh-variable technique generate only thirty tests.

Even if we try to increment the lower and upper bound, the number of generated tests and the time spent will be exactly the same, because our tool will stop as long as all locations are reached and in terms of CBMC it has no difference because do no exist loops.

6.1. Tool Evaluation

Cars

		Cars					
Bound range	Methodology	Computation Time / CPU Time	Number of locations to reach	Percentage of coverage reached	Number of tests	Missed locations	Infeasible set of locations searched
[min:1 max:1]	Token	7s / 0.75s	26	88%	23	[19,22,25]	
	Fresh-Variable Single location	4s / 0.48s	26	77%	8	$\begin{bmatrix} 17,19,21, \\ 22,23,25 \end{bmatrix}$	
	Fresh-Variable Multi-location	3s / 0.48	26	77%	8	$\begin{bmatrix} 17,19,21, \\ 22,23,25 \end{bmatrix}$	5
[min:2 max:2]	Token	8s / 0.75s	26	88%	23	[19,22,25]	
	Fresh-Variable Single location	5s / 0.57s	26	88%	9	[19,22,25]	
	Fresh-Variable Multi-location	6s / 0.61s	26	88%	9	[19,22,25]	8
[min:10 max:10]	Token	9min / 0.8s	26	88%	23	[19,22,25]	
	Fresh-Variable Single location	3min / 0.79s	26	88%	10	[19,22,25]	
	Fresh-Variable Multi-locations	7min / 0.83s	26	88%	9	[19,22,25]	12
[min:1 max:10]	Token	12min / 0.93s	26	88%	23	[19,22,25]	
	Fresh-Variable Single location	6min / 0.76s	26	88%	9	[19,22,25]	
	Fresh-Variable Multi-locations	14min / 1.31s	26	88%	9	[19,22,25]	12

Table 3 The cars evaluation results

The cars case study consists in a function relating three cars, more specifically, their positions and velocities in different time intervals. In each interval the car position is updated depending on the current speed and the velocity might be non deterministically updated.

As we can observe in Table 3, the token methodology performs better when using 1 as lower and upper bound. It can reach 88% of decision coverage, while the other two methodologies reach only 77%.

With respect to the number of generated tests the token methodology is the less efficient. Twenty three tests are generated as opposed to nine in the methodologies based on the fresh-variable techniques for the same result in terms of coverage level.

In general, the methodology which is less time efficient is the token methodology. Something worth to be mentioned is the performance by the fresh-variable methodology for single location when we set the lower and upper bound to ten. It is twice as fast as the fresh-variable methodology for multiple location and three times faster than the token methodology.

Grep

		Grep					
Bound range / Unit	Methodology	Computation Time / CPU Time	Number of locations to reach	Percentage of coverage reached	Number of tests	Missed locations	Infeasible set of locations searched
[min:0 max:0] Single Unit	Fresh-Variable Single location	40mins / 9.85s	59	79.66%	12	(12)[1]	
	Fresh-Variable Multi-location	30min / 8.25s	59	55.93%	7	(26)[1]	32
[min:1 max:1] Single Unit	Fresh-Variable Single location	43mins / 9.99s	59	79.66%	12	(12)[1]	
	Fresh-Variable Multi-location						
[min:0 max:0] Dependency Unit	Fresh-Variable Single location	146mins / 44.15s	306	68.62%	34	(96)[1]	
	Fresh-Variable Multi-location	37min / 9.63s	306	27.77%	7	(221)[1]	32
[min:1 max:1] Dependency Unit	Fresh-Variable Single location	146mins / 44.28s	306	68.62%	34	(96)[1]	
	Fresh-Variable Multi-location						

Table 4 The grep evaluation results

The grep utility is a unix command line tool that prints each line of a text that contains a certain pattern. Its implementation has roughly 2500 lines of code.

To evaluate the grep utility, we had to gather all code into a single file - this is a current restriction of our tool. Moreover, as we have explained inSection 5.5.2, due to CBMC restrictions we were not able to test the token methodology and ended up testing only the methodologies based on the fresh-variable technique. The first two groups of lines in Table 4 are assuming single unit when calculating the level of coverage and the other two groups are assuming dependency unit - see discussion in Section 5.6. The `grep` function in grep utility is being used as the target function.

From the Table 4, we can observe that the fresh-variable for multi-location methodology does not scale even for the case in which loops are unwind only once. In the case of single unit the tool was still able to generate the set of locations, but then it was unable to terminate the computation to generate tests in less then 24 hours. In the case of dependency unit, the tool was unable to generate the set of locations.

If one considers an isolated function to be the smallest unit in a system and if the fresh-variable for single-location is used, the tool is able to reach almost 80% of decision coverage in the case of the

1 Number of locations that were not reached

`grep` function (shown in the first line of the table). This value is kept even if the tool unwinds loops once (shown in the second line of the table). In the case of fresh-variable for multi-location the tool is only able to reach 55.3% of decision coverage if loops are not unwound.

When considering the dependency unit as the criterion, we are able to reach more 68% of decision coverage even if loops are not unwound. This means that almost 69% all locations in the `grep` function and in the functions that are invoked through function calls are reached. Nonetheless, when using the fresh-variable for multi-location, the tool only covers 27.77% of the code.

6.2 Global Analysis

In the previews section, we made some observations about the results obtained for each case study separately. In this section we make a global analysis taking into account all the cases studies and making some observations about the results we obtained.

The first thing worth of note is that the token methodology can reach higher levels of decision coverage with smaller bounds than the methodologies based on the fresh-variable technique. The explanation for this behaviour is that the execution traces produced by CBMC do not need to reach the end of the program. On contrary, when using the methodologies based on the fresh-variable technique, the produced traces need to reach the end of the program. See Section 4.1, where both techniques are described. The bubble sort case study is excellent example as it requires at least 16 iteration so the CBMC be able to produce a trace using the fresh variable technique.

Besides the previous limitation, the methodologies based on the fresh-variable technique are more time efficient and also produce less redundant tests. The case study that clearly shows this behaviour is the bubble sort function - the methodologies based on the fresh-variable technique generate only one test that reaches all locations. On the other side the token methodology produces as many tests as the number of locations - seven in total. Nonetheless, the same behaviour is observed in the other case studies.

For the first three case studies, when comparing the methodologies based on the fresh-variable technique we cannot see much difference. Both methodologies generate slightly the same number of tests in the same period of time. However, when looking at the fourth case study we can observe that the fresh-variable for multi-location did not scale for long execution runs, as it is the case when the tool unwinds loops once. Note also that when the technique is able to generate tests, those do not reach the same level of coverage as the tests produced by the fresh-variable for single-location. However, we should note that this is not a limitation of the methodology. Instead it is a limitation of the current implementation because we are still not supporting goto statements. When creating set of locations we just ignore the semantics of the goto statements.

6.3 CONCLUSION

The main contribution of this dissertation is the release of an automated test data generator for programs in C language using the software bounded model checker CBMC. Initially we aimed to extend the methodology presented in Angeletti et al. [2], by generating tests to reach other coverage criteria (the methodology presented in [2] only supports decision coverage). However, due to some setbacks, we ended up focusing on improving the methodology to generate tests to reach decision coverage and we only discuss how the condition coverage and condition/decision coverage criteria could be implemented. We ended up with three different methodologies. Comparatively to the methodology in presented [2], our methodologies do not relay on the use of code coverage analysis tools.

Initially, we tried to reproduce the methodology described by Angeletti et al. [2]. However, we did not find a suitable external coverage analysis tool and ended up developing the so called token methodology. This methodology differs from the original in some aspects. As opposed to the original technique, our technique always generate as many tests as the number of locations to be reached. This happens because the original technique depends on an external tool, and once the external tool signals that all locations were reached the test generation process can stop. However, both this methodologies obtains the same results (in time, tests, and coverage achieved) whenever the original methodology has no need to call the external tool or whenever the token methodology has no need to increase the bound.

The results produced by the token methodology did not satisfy us. The only way to improve the results would be through knowledge of the locations achieved by each test. To solve such matter, we developed a new technique to signalize the locations, which we end up calling the fresh-variable technique. Based in this technique, we developed other two new methodologies, the fresh-variable for single location and the fresh-variable for multi-locations, which were implemented in our tool.

Both methodologies based on the fresh-variable technique produce similar results and perform significantly better than the token methodology in the cases that the considered bound allows for full executions to be considered. Note that when using the fresh-variable technique only traces containing a complete path of the target function are returned by CBMC. When using the signalling technique from the token methodology, the execution traces do not necessarily need to reach the end of the program. Also recall that the results obtained when the fresh-variable technique is applied are highly dependent on the way that locations or set of locations are chosen. Implementing heuristics can lead improvements on the number of generated tests and also on their redundancy. For instance, for the fresh-variable methodology using single location, we used the heuristic that chooses the deeper location in the program structure and also the one that is in the last part of the program. We observed that if we changed the heuristic applied, for instance to select the location placed first in the code, the number of generated tests increases and as consequence the number of redundant tests also increases.

The grep utility evaluation intended to test the tool capability and effectiveness in large and complex applications source code. Unfortunately, due to CBMC restrictions, we were not able to use the

token methodology and ended up using only the methodologies based on the fresh-variable technique. Although we only used small bounds due to state space explosion, we managed to obtain high percentage of code coverage. For less complex code, the tool performed very well obtaining 100% of code coverage code coverage for the exception of the cars function which failed to reach three location we believe to be unreachable (actually CBMC failed to find execution traces reaching those locations even when we set the bounds up to 200).

6.4 Future Work

We have developed the AuTGen-C tool which is available and ready to be used. The preliminary experiments with our case studies were very encouraging, but there are still some features that can be improved.

In the current version of the tool the fresh-variables methodology for multi-locations does not deal with *goto* statements. We did not implement that for lack of time, but we do not anticipate major difficulties in doing that.

Another feature to be implemented in a future version of the tool is the generation of tests for other coverage criteria. We have addressed this topic in Chapter 4, concerning condition and condition/decision coverage, but a more detailed study has to be done before the implementation.

Despite the success of the experiments with the case studies here described, further experiments should be carried out with different kinds of C programs and with C programs of bigger dimension. Moreover, we should also make a study comparing the AuTGen-C tool with other existing tools of test data generation for C programs. The lessons learned from that study should guide other possible improvements for the AuTGen-C platform.

Another line of work is to analyse the quality of the tests generated by the different methodologies implemented in the tool and to propose improvements to the algorithms in order to minimize the number of tests generated without losing coverage. In particularly, we should investigate new methodologies, based in the fresh-variable technique, with the aim of producing set of tests without redundancy.

An interesting feature to be added to this tool is the automatic inference of the minimum bound to achieve the required coverage level. This could be done through the use of heuristics such as those reported in [23].

BIBLIOGRAPHY

[1] Damiano Angeletti, Enrico Giunchiglia, Massimo Narizzano, Gabriele Palma, Alessandra Puddu, and Salvatore Sabina. Improving the Automatic Test Generation process for Coverage Analysis using CBMC. (December), 2009.

[2] Damiano Angeletti, Enrico Giunchiglia, Massimo Narizzano, Alessandra Puddu, and Salvatore Sabina. Using bounded model checking for coverage analysis of safety-critical software in an industrial setting. *J. Autom. Reason.*, 2010.

[3] Christel Baier and Joost-Pieter Katoen. *Principles of Model Checking (Representation and Mind Series)*. The MIT Press, 2008.

[4] Mohammed Bekkouche. Exploration of the scalability of locfaults approach for error localization with while-loops programs. 2015.

[5] Armin Biere, Alessandro Cimatti, Edmund Clarke, and Yunshan Zhu. Symbolic model checking without BDDs, 1999.

[6] E. Clarke, D. Kroening, and K. Yorav. Behavioral consistency of C and Verilog programs using bounded model checking. *Proceedings 2003. Design Automation Conference (IEEE Cat. No.03CH37451)*, 2003.

[7] Edmund Clarke, Daniel Kroening, and Flavio Lerda. A Tool for Checking ANSI-C Programs. *Tools and Algorithms for the Construction and Analysis of Systems*, 2004. ISSN 03029743.

[8] Edmund M. Clarke, Orna Grumberg, and David E. Long. Model checking and abstraction. *ACM Trans. Program. Lang. Syst.*, 1994.

[9] D. Gelperin and B. Hetzel. The growth of software testing. *Communications of the ACM*, June 1988.

[10] Bhargav S. Gulavani, Supratik Chakraborty, Aditya V. Nori, and Sriram K. Rajamani. Automatically refining abstract interpretations. In *Proceedings of the Theory and Practice of Software, 14th International Conference on Tools and Algorithms for the Construction and Analysis of Systems*, TACAS'08/ETAPS'08, 2008.

[11] D. Huizinga and A. Kolawa. *Automated Defect Prevention: Best Practices in Software Management*. Wiley, 2007. ISBN 9780470165164.

[12] Daniel Jackson. Dependable software by design, 2006. URL http://www.cs.virginia.edu/~robins/Dependable_Software_by_Design.pdf.

[13] Ranjit Jhala and Rupak Majumdar. Software model checking. *ACM Computing Surveys*, 41, 2009.

[14] Richard M. Karp. Reducibility among combinatorial problems. In Raymond E. Miller and James W. Thatcher, editors, *Complexity of Computer Computations*, The IBM Research Symposia Series. Plenum Press, New York, 1972.

[15] Hayhurst Kelly J., Veerhusen Dan S., Chilenski John J., and Rierson Leanna K. A practical tutorial on modified condition/decision coverage. Technical report, 2001.

[16] MSDN Microsoft Developer Network. Integration testing. URL http://msdn.microsoft.com/en-us/library/aa292128%28v=vs.71%29.aspx.

[17] Glenford J. Myers, Corey Sandler, and Tom Badgett. *The Art of Software Testing*. John Wiley & Sons, 2004.

[18] S. Naik and P. Tripathy. *Software Testing and Quality Assurance: Theory and Practice*. ISBN 9780470382837.

[19] Johanna Rothman. What does it cost to fix a defect? 2002. URL http://www.stickyminds.com/article/what-does-it-cost-fix-defect.

[20] G. Michael Schneider, Johnny Martin, and W. T. Tsai. An experimental study of fault detection in user requirements documents. *ACM Trans. Softw. Eng. Methodol.*, pages 188–204, 1992.

[21] NASA TECHNICAL STANDARD. Facility System Safety Guidebook. *Analysis*, (January), 1998.

[22] Jonette M. Stecklein, Jim Dabney, Brandon Dick, Bill Haskins, Randy Lovell, and Gregory Moroney. Error cost escalation through the project life cycle, 2004.

[23] Hitesh Tahbildar and Bichitra Kalita. Heuristic approach of automated test data generation for program having array of different dimensions and loops with variable number of iteration. 2010.

[24] G. Tassey. The economic impacts of inadequate infrastructure for software testing, 2002. URL http://www.nist.gov/director/planning/upload/report02-3.pdf.