Fault-tolerant UIO Sequences in Finite State Machines

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Abstract

The central idea in the paper is to define the concept of *strength* of a UIO sequence in verifying a state in a faulty implementation. The strength of a UIO sequence is a quantitative measure of the number of output faults required to render the verification power of the sequence ineffective. Thus, UIO sequences of higher strengths can tolerate more output faults while verifying a state. We present an algorithm to compute all UIO sequences of maximal strength in a state machine.

Key Words: FSM, Protocol Testing, State Verification, UIO Sequence, Fault Detection, Strength of a UIO Sequence, Fault-tolerant UIO Sequence

1 Introduction

Testing of communication protocols remains to be a subject of continued research. The four test sequence generation methods are the transition tour, the D-, W-, and U-method [SL 89]. The last three are called *formal* methods, because they verify the next state of a transition. State verification is the main argument in favor of using formal methods over the transition tour method. However, a verification sequence fails to verify the next state of a transition if the verification sequence *loses its strength* to verify the state due to faults in the implementation. By *losing strength*, we mean the verification sequence in the specification is not a verification sequence in the implementation. Chan, *et. al.* showed how a UIO sequence in a specification no more remains a UIO sequence in a faulty implementation [CVI 89].

Once a UIO sequence loses its property to verify a state, there is the danger of faults being undetected. However, in a faulty implementation, there is every likelihood that some UIO sequences lose their property. Given an FSM, UIO sequences can be considered as static properties of the FSM. Or, we can say that the verification power of UIO sequences are static properties of the FSM. In our opinion, on the other hand, faults in an implementation are dynamic “properties” of the implementation. These are dynamic in the sense that one specification FSM can have multiple faulty implementations with one implementation being different from another. While using UIO sequences for state verification, we are faced with the problem of coping with dynamic properties of implementations using the static properties of a specification FSM. In this paper, we will find answers to the following questions on UIO sequences.

- (i) Assuming that an implementation could be arbitrarily faulty, what is the measure of *goodness* of a UIO sequence?
- (ii) In the presence of faults, how good are UIO sequences of minimal lengths?
- (iii) Can non-minimal UIO sequences with additional properties verify states of a faulty implementation?
- (iv) Are two UIO sequences of identical length for the same state equally good?
- (v) How to compute the upper bound on the measure of goodness of UIO sequences in a given machine?

The above questions lead to a notion of *fault-tolerance* capability of UIO sequences. That is, to what extent can a UIO sequence tolerate implementation faults and retain its state verification property? We begin our study with a review of why a UIO sequence fails to verify a state in an implementation. Such a review motivates us to define the concept of *strength* of a UIO sequence. The strength of a UIO sequence is a quantitative measure of its fault-tolerant capability.

In Section 2, we state some graph theoretic terms, a basic test sequence, and a fault model. In Section 3, we review how state faults can be masked under various conditions. In Section 4, we present the idea of fault-tolerant UIO sequences and present an algorithm to generate all UIO sequences of maximal strengths. Some concluding remarks are given in Section 5.

2 Protocol Specification and Test Sequence

We organize this section in three parts. In the first part, we present a few FSM and graph-theoretic terms. The general structure of a test sequence is outlined in the second part. Assumptions about an implementation and a fault model are stated in the third part.

2.1 FSM and Graph-theoretic Terms

A finite-state machine M is a tuple: $M = (S, I, O, \delta, \lambda)$, where $S = \{s_1, \dots, s_n\}$ is a finite set of states; $I = \{a_1, \dots, a_p\}$ is a finite set of inputs; $O = \{b_1, \dots, b_r\}$ is a finite set of outputs; $\delta : S \times I \rightarrow S$ is the state transition function; and $\lambda : S \times I \rightarrow O$ is the output function.

For convenience we extend the domain of λ and δ from an input symbol to a string of symbols. For instance, for state s_i and input sequence $x = a_1, \dots, a_k$, the corresponding output sequence is denoted by $\lambda(s_i, x)$ and the final state is denoted by $\delta(s_i, x)$. Also, we extend the transition and output functions from single states to sets of states. That is, if Q is a set of states and x is an input sequence, then $\delta(Q, x) = \{\delta(s, x) | s \in Q\}$, and $\lambda(Q, x) = \{\lambda(s, x) | s \in Q\}$.

An FSM M is viewed as a directed graph $G = (V, E)$, where the set of vertices $V = \{v_1, \dots, v_n\}$ represents the set S of states of M , and a set of edges $E = \{(v_j, v_k; a/b) | v_j, v_k \in V\}$ represents all transitions in M . Each edge $e_{jk} = (v_j, v_k; a/b) \in E$ represents a state transition from s_j to s_k with input a and output b . For the sake of brevity, when λ and δ are known, we also denote a transition by a pair (v_j, a) . Notation $x@y$ denotes the *concatenation* of strings x and y .

We denote an implementation of M by $M' = (S, I, O', \delta', \lambda')$. Though we do not know the next state function δ' and output function λ' of the implementation, we use them only for explanatory purpose and not to compute any state or output.

2.2 Basic Test Sequence

In FSM-based testing, the basic strategy is to apply the following three steps for all states and inputs. First, move the implementation to some state s_i and apply an input a . Second, verify that the implementation produces the desired output $\lambda(s_i, a)$. Third, verify that the implementation has moved to state $\delta(s_i, a)$ by applying

a state verification sequence to the implementation and observing the corresponding response.

Let $TX(s_j, s_i)$ denote an input sequence that transfers machine M from state s_j to s_i . Let $VS(s_k)$ denote an input sequence that verifies that M is in state s_k . We leave out the output parts from these sequences, because they can be readily computed from the specification machine. Let $\Omega(s_k, VS(s_k))$ denote the set of transitions executed by M while $VS(s_k)$ is applied in state s_k .

Assume that implementation M' is in a known state s_j and we want to test the output and next state functions associated with transition (s_i, a) . Thus, a basic test sequence for state s_i and input a is defined as an input sequence:

$BTS(s_i, a) = TX(s_j, s_i)@a@VS(s_k)$, where $s_k = \delta(s_i, a)$.

The three commonly used state verification sequences are distinguishing sequence [KOH 78], Unique Input/Output (UIO) sequence [SD 88], and pair-wise distinguishing sequence (W-sequence) [CHO 78], [FBK 91]. The shortest path consisting of verified transitions from s_j to s_i or a *reset* input is generally selected to be a transfer sequence $TX(s_j, s_i)$.

The subsequence $a@VS(s_k)$ of $BTS(s_i, a)$ is largely known as a *test segment*. Thus, a complete test sequence for a machine is an appropriate concatenation of a collection of test segments and transfer sequences. For the purpose of minimizing the length of the test sequence, various kinds of optimization techniques involving *overlapping* of test segments can be used [ADLU 91], [MP 93], [UZ 93].

2.3 Assumptions and Fault Model

We assume that a protocol behavior is modeled as a completely specified, deterministic, reduced, and strongly connected finite state machine. We make the following assumptions about an implementation.

- (i) An implementation has the same number of states as the specification.
- (ii) Faults in an implementation are restricted to output (λ) and state (δ) functions.
- (iii) All the faults in an implementation are *permanent*.

3 Fault Masking

Assume that an implementation is in state s_i and we want to test the output and next state functions for input a in state s_i . In the UIO method, we need a basic test sequence of the following form:

$BTS(s_i, a) = a@I'(s_k)$,

where $s_k = \delta(s_i, a)$ and $I'/\lambda(s_k, I')$ is a UIO sequence for state s_k .

An output fault can be readily detected if the observed output $\lambda'(s_i, a)$ is not equal to $\lambda(s_i, a)$. However, detecting a state fault is a non-trivial task in spite of using a

state verification sequence. This is due to the fact that one fault can mask another [CVI 89], [LS 92], [MP 94]. In the following, we illustrate three kinds of masking:

K1: Output faults in some transitions can mask a state fault in some other transition;

K2: State faults in some transitions can mask a state fault in some other transition.

K3: A state fault masks itself depending on the structure of the FSM.

A. K1 and K2 Type of Fault Masking

Consider the following scenario. Let the implementation of $\delta(s_i, a)$ be faulty, that is, $\delta(s_i, a) = s_k$, $\delta'(s_i, a) = s_j$, and $s_j \neq s_k$. Since we are interested in verifying state s_k , let $I'/\lambda(s_k, I')$ be a UIO sequence for state s_k . Now we have the following four cases.

Case 1: Output functions of all transitions in $\Omega(s_j, I'(s_j))$ are correctly implemented. Thus, $\lambda'(s_j, I') = \lambda(s_j, I')$.

Case 2: Some output functions of transitions in $\Omega(s_j, I'(s_j))$ are faulty such that $\lambda'(s_j, I') = \lambda(s_k, I')$.

Case 3: All state transitions in $\Omega(s_j, I'(s_j))$ are correctly implemented.

Case 4: Some state transitions in $\Omega(s_j, I'(s_j))$ are faulty, but the associated outputs are correctly implemented.

In *Case 1*, $\lambda(s_k, I') \neq \lambda'(s_j, I')$, because $I'/\lambda(s_k, I')$ is a UIO sequence for s_k . Since the observed sequence $\lambda'(s_j, I')$ is different from the expected sequence $\lambda(s_k, I')$, we can deduce that implementation of $\delta(s_i, a)$ is faulty.

However, in *Case 2*, faults in the implementation of output functions of some transitions in $\Omega(s_j, I'(s_j))$ produce an expected output sequence, thereby effectively masking the state fault $\delta'(s_i, a) = s_j$. Thus, *Case 2* results in a K1 type of fault masking.

The implication of *Case 3* is similar to that of *Case 1* or *Case 2* depending on the correctness of implementation of the output functions.

Case 4 leads to a K2 type of fault masking, because the correct output of the faulty transitions in $\Omega(s_j, I'(s_j))$ produce the expected output, thereby effectively masking the fault under consideration.

Example 1: In Fig. 1, we illustrate the K1 and K2 types of fault masking. Fig. 1(a) shows a part of a specification. We assume that abc/xyz_1 and abc/xyz_2 are the UIO sequences of states s_2 and s_3 , respectively. Figs. 1(b) and (c) show two kinds of erroneous implementations. We focus on the implementation of the edge $(s_1, s_2; d/w)$. In both the implementations, edge $(s_1, s_2; d/w)$ has been implemented as $(s_1, s_3; d/w)$. We denote the faulty implementation of this transition by fault

$f1$. Additionally, edge $(s7, s9; c/z2)$ has been implemented as $(s7, s9; c/z1)$ with an output fault in Fig. 1(b). This output fault is denoted as $f2$. Edge $(s5, s7; b/y)$ has been implemented as $(s5, s6; b/y)$ with a state fault in Fig. 1(b). This output fault is denoted as $f3$. It is easy to see that the state fault $f1$ has been masked by the output fault $f2$ and state fault $f3$ in Fig. 1(b) and Fig. 1(c), respectively.

B. K3 Type of Fault

In the $K3$ type of fault [CVI 89], a state fault can mask itself depending on the structure of the machine. Let the transition $(s_i, s_j; a/b)$ be implemented as $(s_i, s_i; a/b)$. If there exists an input sequence I' such that

- (i) $\lambda(\delta(s_j, a), I') = \lambda(s_i, I')$ and
- (ii) $a@I'/\lambda(s_j, a@I')$ is a UIO sequence for s_j ,

the state fault masks itself. Thus, given an FSM and a UIO sequence for each state, it is possible to check whether $K3$ types of faults in an implementation could go undetected. The simplest way to avoid the $K3$ type of fault masking is not to select a UIO sequence satisfying the above properties.

In the following, we discuss an approach to cope with the $K1$ type of fault masking by introducing the concept of *strength* of a UIO sequence.

Figure 1: Illustration of Fault Masking.

4 Fault-tolerance Capability of a UIO Sequence

In this section, we define the *strength* of a UIO sequence and give an algorithm to compute all UIO sequences of maximal strength in an FSM.

4.1 Strength of a UIO Sequence

Definition: Given a state s in a machine M and input sequence I' , the *transition trace* $TT(s, I')$ is defined as the sequence of transitions traversed in M as a result of applying I' at s .

Definition: Let s_i and s_j be two states and I' be an input sequence in a machine M . Let $O_i = \lambda(s_i, I')$ and $O_j = \lambda(s_j, I')$. The *difference* between the two output sequences O_i and O_j , denoted by $O_i \sim O_j$, is defined as a sequence of 0 and 1, such that the k th. symbol of $O_i \sim O_j$ is a 1 if and only if:

- (i) the k th transitions in $TT(s_i, I')$ and $TT(s_j, I')$ have different outputs and
- (ii) in case the k th. transition in $TT(s_i, I')$ is identical to any of its predecessors in $TT(s_i, I')$, its identical predecessor has not contributed a 1 to $O_i \sim O_j$, and
- (iii) in case the k th. transition in $TT(s_j, I')$ is identical to any of its predecessors in $TT(s_j, I')$, its identical predecessor has not contributed a 1 to $O_i \sim O_j$.

The number of 1s in $O_i \sim O_j$ is called the *degree of difference* between the two output sequences and is denoted by $DoD(O_i, O_j)$.

Remark: In the above definition, the first condition for assigning a 1 to the k th. entry of the difference sequence is obvious. The last two conditions allow us to consider the output fault of a transition exactly once, even though the transition may appear many times in the transition trace.

Definition: Let $M = (S, I, O, \delta, \lambda)$ be an FSM. The *strength* of a UIO sequence $I'/\lambda(s_i, I')$ for state s_i is the *minimum* of $DoD(\lambda(s_i, I'), \lambda(s_j, I'))$, $\forall s_j \in S$ and $s_j \neq s_i$. We denote the strength of a UIO sequence UIO_k for state s_i by $strength(s_i, UIO_k)$.

Remark: Obviously, the minimum strength of any UIO sequence for any state is one. In case a state has many UIO sequences, their strengths could be different.

The motivation for defining the strength of a UIO sequence is as follows. Consider transition $(s_i, s_j; a/b)$ which has been incorrectly implemented as $(s_i, s_k; a/b)$ with a state fault. Assume that $UIO_{s_j} = I'/\lambda(s_j, I')$ is used to verify state s_j . If $strength(s_j, UIO_{s_j}) = 1$, one output fault in the set of transitions $\Omega(s_k, I'(s_k))$ is necessary to mask the state fault. If $strength(s_j, UIO_{s_j}) = 2$, two output faults in the set of transitions $\Omega(s_k, I'(s_k))$ are necessary to mask the state fault. In general, if $strength(s_j, UIO_{s_j}) = m, m \geq 1$, $m - 1$ output faults in $\Omega(s_k, I'(s_k))$ can mask the state fault. Thus, higher the strength of a UIO sequence, more output faults are necessary to mask a state fault. Theoretically, in order to detect the state fault, we need a UIO sequence whose strength is more than the number of output faults in an implementation.

Remark: All minimal length UIO sequences have a strength of one. Thus, a single output fault can render them ineffective.

Example 2: Consider machine $M1$ and its implementation in Figs. 2(a) and (b), respectively. Transition $(s_6, s_3; b/1)$ has been incorrectly implemented with a

state fault as $(s_6, s_5; b/1)$ and transition $(s_1, s_3; a/1)$ has been incorrectly implemented with an output fault as $(s_1, s_3; a/0)$. We want to test the implementation of state transition $(s_6, s_3; b/1)$. We will consider two cases, such that the first case involves a UIO sequence with a strength of *one* and the second case involves a UIO sequence with a strength of *two*. In both the cases, we assume that the implementation is in state s_6 .

Case 1: Consider the minimal length UIO sequence $aaa/000$ for state s_3 .

$$\begin{aligned}\lambda(s_1, aaa) &= 100, \lambda(s_2, aaa) = 010, \\ \lambda(s_3, aaa) &= 000, \lambda(s_4, aaa) = 110, \\ \lambda(s_5, aaa) &= 001, \lambda(s_6, aaa) = 101. \\ DoD(\lambda(s_3, aaa) \sim \lambda(s_1, aaa)) &= 1, \\ DoD(\lambda(s_3, aaa) \sim \lambda(s_2, aaa)) &= 2, \\ DoD(\lambda(s_3, aaa) \sim \lambda(s_4, aaa)) &= 2, \\ DoD(\lambda(s_3, aaa) \sim \lambda(s_5, aaa)) &= 1, \\ DoD(\lambda(s_3, aaa) \sim \lambda(s_6, aaa)) &= 2.\end{aligned}$$

Therefore, $strength(s_3, aaa/000) = 1$. A basic test sequence to test the implementation of $(s_6, s_3; b/1)$ is:

$$BTS(s_3, b) = b@aaa,$$

where input b is expected to take the implementation to state s_3 and the aaa sequence is expected to verify that the implementation indeed moves to state s_3 . However, input b takes the implementation to state s_5 and the sequence aaa in state s_5 produces the "expected" output 000, because transition $(s_1, s_3; a/1)$ has been implemented as $(s_1, s_3; a/0)$ with an output fault. Thus, the basic test sequence fails to detect the state fault due to a $K1$ type of fault masking.

Case 2: Consider a non-minimal length UIO sequence $aaaba/00010$ for state s_3 .

From $M1$,

$$\begin{aligned}\lambda(s_1, aaaba) &= 10001, \lambda(s_2, aaaba) = 01001, \\ \lambda(s_3, aaaba) &= 00010, \lambda(s_4, aaaba) = 11010, \\ \lambda(s_5, aaaba) &= 00111, \lambda(s_6, aaaba) = 10111. \\ DoD(\lambda(s_3, aaaba) \sim \lambda(s_1, aaaba)) &= 3, \\ DoD(\lambda(s_3, aaaba) \sim \lambda(s_2, aaaba)) &= 3, \\ DoD(\lambda(s_3, aaaba) \sim \lambda(s_4, aaaba)) &= 2, \\ DoD(\lambda(s_3, aaaba) \sim \lambda(s_5, aaaba)) &= 2, \\ DoD(\lambda(s_3, aaaba) \sim \lambda(s_6, aaaba)) &= 3.\end{aligned}$$

Therefore, $strength(s_3, aaaba/00010) = 2$. A basic test sequence to test the implementation of $(s_6, s_3; b/1)$ is:

$$BTS(s_3, b) = b@aaaba,$$

where the first input b is expected to take the implementation to state s_3 and the $aaaba$ sequence is expected to verify that the implementation indeed moves to state s_3 . However, input b takes the implementation to state s_5 and the sequence $aaaba$ in

state s_5 produces the output 00011. Since the output of the implementation 00011 differs from the expected output $\lambda(s_3, aaaba) = 00010$, one can conclude that there is a state fault in the implementation of transition $(s_6, s_3; b/1)$. That is, the basic test sequence using a UIO sequence of strength *two* can tolerate *one* output fault in the implementation of any transition.

Figure 2: A specification [UZ 93] and a faulty implementation.

4.2 Generation of UIO Sequences of Maximal Strength

One can obtain UIO sequences of minimal lengths using the algorithm in [SD 88]. Given a UIO sequence for a state, one can always obtain a UIO sequence of longer length for the same state and check its strength. In order to generate UIO sequence of higher strength, the UIO sequence needs to be made longer. However, it is difficult to define a termination condition for this approach.

Therefore, we will take a different approach to obtaining UIO sequences of higher strength. We will modify another algorithm to compute UIO sequences [NAIK 94] for this purpose. We first introduce a *path vector* and *perturbation* of a path vector. Based on the perturbation idea, next we define a *UIO-tree*. We incorporate three termination conditions into the perturbation process so that the algorithm terminates after generating all UIO sequences of maximal strengths.

Definition: Given an FSM M , a *path vector* (PV) is a collection of state pairs, $(v_1/v'_1, \dots, v_i/v'_i, \dots, v_k/v'_k)$, with the following properties:

- (1) v_i and v'_i denote the head and tail state, respectively, of a path, where a path is a sequence of state transitions and
- (2) an identical sequence of input/output is associated with all the paths in the path vector.

Given a path vector $PV = (v_1/v'_1, \dots, v_i/v'_i, \dots, v_k/v'_k)$, the *initial vector* (IV) is the collection of head states of PV , that is $IV(PV) = (v_1, \dots, v_i, \dots, v_k)$. Similarly, the *current vector* (CV) is the collection of tail states of PV , that is $CV(PV) = (v'_1, \dots, v'_i, \dots, v'_k)$.

A path vector is said to be a *singleton* vector if it contains exactly one state pair. A path vector $PV = (v_1/v'_1, \dots, v_i/v'_i, \dots, v_k/v'_k)$ is said to be a *homogeneous* vector if all members of $CV(PV)$ are identical. It may be noted that a singleton vector is also a homogeneous vector.

For an n -state machine, we define a unique *initial* path vector: $(s_1/s_1, \dots, s_i/s_i, \dots, s_n/s_n)$ such that a *null* path is associated with all state pairs.

Now we introduce the idea of *vector perturbation*. That is, given a path vector PV and an edge label a/b , how to compute a new vector PV' from PV and a/b .

Definition: Given a path vector $PV = (v_1/v'_1, \dots, v_i/v'_i, \dots, v_k/v'_k)$ and an edge label a/b , *perturbation* of PV with respect to edge label a/b , denoted by $PV' = pert(PV, a/b)$ is defined as:

$$PV' = \{v_i/v'_i | v''_i = \delta(v'_i, a) \wedge \lambda(v'_i, a) = b \wedge v_i/v'_i \in PV\}.$$

Given a reduced machine and its initial path vector, we can infinitely perturb all the path vectors for all edge labels. One can imagine the perturbation function $PV' = pert(PV, a/b)$ as an arc from a node PV to a new node PV' with edge label a/b . Also, given a PV and a set of edge labels L , we can arrange the new $|L|$ nodes $pert(PV, a/b), \forall a/b \in L$ on one level. That is, all the path vectors of a given machine can be arranged in the form of a tree with successive levels $1, 2, \dots, \infty$. Such a tree is called a *UIO-tree*.

Note: In the graphical representation of a path vector $PV = (v_1/v'_1, \dots, v_i/v'_i, \dots, v_k/v'_k)$ in a UIO-tree, we represent PV in two rows of states. The top row denotes $IV(PV)$ and the bottom row denotes $CV(PV)$.

Theoretically, a UIO-tree is a tree with infinite levels. However, we need to prune the tree based on some conditions, called *pruning* conditions. After each perturbation $PV' = pert(PV, a/b)$, we check the following pruning conditions:

- C1:** $CV(PV')$ is a homogeneous vector containing more than one element.
- C2:** On the path from the initial node to PV , there exists PV'' such that $PV' \subseteq PV''$.
- C3:** On the path from the initial node to PV , there exists a singleton node and a node PV'' such that $PV' \subseteq PV''$. (Note: the singleton node and PV'' can be the same node.)

If one of the pruning conditions is satisfied, we declare PV' to be a *terminal* node. Now we explain why $C1$, $C2$ and $C3$ are the required termination conditions. Let us consider condition $C1$. If $CV(PV')$ is a homogeneous vector containing more than one element, any further perturbation of the path from the initial node to PV' will not lead to any UIO sequence. Condition $C2$ states that there is no need of perturbing a node if the node or a superset of the node appears before. This is because, if the node or its superset appears before, then it has already been perturbed in all possible ways and perturbing it once again will not lead to new information. Condition $C3$ deals with UIO sequences. If a UIO-tree contains a singleton node, then the sequence of input/output associated with the path from the initial node to the singleton node

is a UIO sequence for the *head* state of the node. If we are simply interested in UIO sequences of minimal lengths, we can stop perturbing a singleton node [NAIK 94]. However, we are interested in UIO sequences of maximal strengths. Therefore, we further perturb a singleton node until we know that further perturbation will not add extra information to the UIO sequence. This happens when the singleton node appears before either as itself or as a subset of a larger node. In the rest of the paper, we use the terms *path vector* and *node* in a UIO-tree interchangeably. In the following, we present an algorithm to compute maximal strength UIO sequences.

Algorithm 1: Generating UIO Sequences of Maximal Strength.

Input: $M = (S, I, O, \delta, \lambda)$ and L .

Output: UIO sequences of maximal strengths.

Method: Execute the following steps.

Step 1: Let Ψ be the set of nodes denoting path vectors in the UIO-tree. Initially, Ψ contains the initial vector marked as *non-terminal*.

Step 2: Find a non-terminal member $\psi \in \Psi$ which has not been perturbed. If no such member exists, then go to **Step 5**.

Step 3: Compute $\psi' = \text{pert}(\psi, a_i/b_i)$ and add ψ' to Ψ , $\forall a_i/b_i \in L$. Mark ψ to be perturbed. Update the UIO-tree.

Step 4: If $\text{pert}(\psi, a_i/b_i)$, computed in Step 3, satisfies condition $C1$, $C2$, or $C3$, then mark $\text{pert}(\psi, a_i/b_i)$ as a *terminal* node and go to Step 2.

Step 5: Collect all the UIO sequences for every state and compute their strengths.

Step 6: If a state has at least one UIO sequence, select a UIO sequence of maximal strength. After selecting UIO sequences of maximal strength, terminate the algorithm. **End of Algorithm 1**

Theorem: Given a machine $G = (V, E)$, a state v has a UIO sequence *iff* the UIO-tree has a singleton node ψ such that $v = IV(\psi)$.

A proof of the above theorem can be found in [NAIK 94]. Obviously, the algorithm has an exponential complexity. Termination of the algorithm is guaranteed by the three conditions $C1$, $C2$, and $C3$.

Example 3: We applied Algorithm 1 to the specification machine of Fig. 2 to compute the UIO-tree. A part of the UIO-tree is shown in Fig. 3. Node s_3/s_1 is a singleton node indicating that the sequence of input/output *aaa/000* leading from the initial node to s_3/s_1 is a UIO sequence of minimal length for state s_3 . However, to obtain UIO sequences of higher strength, we further perturb node s_3/s_1 as shown in Fig. 3 to obtain nodes s_3/s_3 and s_3/s_5 . Node s_3/s_3 is a terminal node because condition $C3$ is satisfied. Node s_3/s_5 is further perturbed to obtain nodes s_3/s_2 and s_3/s_6 . Node s_3/s_2 is a terminal node because condition $C3$ is satisfied. We continue perturbing node s_3/s_6 to obtain nodes s_3/s_2 and node s_3/s_3 , which are both terminal nodes. For machine $M1$, the maximal strength of any UIO sequence for any state is two.

Figure 3: A Partial UIO-tree for specification machine M1.

5 Concluding Remarks

In this paper, we discussed how output and state faults can mask some other state faults by rendering the state verification power of a UIO sequence ineffective. The idea of strength of a UIO sequence was useful in defining the fault-tolerance capability of UIO sequences. UIO sequences of higher strengths are generally longer than the minimal length sequences. Since a minimal length UIO sequence has a strength of one, a single output fault can easily render the UIO sequence useless! Since fault detection, rather than short execution time, is presumed to be the main objective of testing, using the minimal length UIO sequences does not seem to be a good idea. UIO sequences of maximal strengths, though longer than the minimal length UIO sequences, are better than the minimal length UIO sequences.

We believe that our work will lead to new research on test generation involving minimization of test sequences with maximal fault detection for a given FSM specification. Presently, the idea of overlapping of test segments is widely used in minimizing a test sequence. However, our work reveals the requirement for a new way of scheduling test segments.

As an extension of our work, one can apply the fault-tolerance idea to other state verification techniques. In our opinion, this work will provide a quantitative and formal basis for comparing the fault detection capabilities of test sequences generated using the D-, W-, and U-methods. More research is required to be done to generate UIO sequences that can tolerate both output and state faults.

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