Test Sequence Generation Using Multiple Unique State Signature (MUSS)

Yoon-Hee Jung and Beom-Kee Hong

Abstract

A procedure presented in this paper generates test sequences to check the conformity of an implementation with a protocol specification, which is modeled as a deterministic finite state machine (FSM). Given a FSM, a common procedure of test sequence generation, first, constructs a directed graph which edges include the state check after each transition, and produces a symmetric graph G* from and, finally, finds a Euler tour of G*. We propose a technique to determine a minimum-cost tour of the transition graph of the FSM. The proposed technique using Multiple Unique State Signature (MUSS) solves an open issue that one MUIO sequence assignment may lead to two more edges of unit cost being replicated to form G* while an optimal assignment may lead to the replication of a single edge of high cost. In this paper, randomly generated FSMs have been studied as test cases. The result shows that the proposed technique saves the cost 4~28% and 2~21% over the previous approach using MUIO and MUSP, respectively.

I. Introduction

Test Sequence generation for conformance testing has been widely advocated for ensuring that protocol implementations are consistent with their specifications[3]. Several approaches have been developed for protocol conformance testing[1-6]. These techniques are based on an approximation algorithm which guarantees that each transition of the specified FSM is traversed at least once.

In[2], the concept of state signature called the Unique Input/Output sequence is proposed. A UIO sequence verifies that the protocol implementation is in an expected state. The UIO sequence approach was combined with the Rural Chinese Postman(RCP) algorithm to provide a robust and compact test sequence[1]. When a graph G is strongly connected and symmetric, the RCP problem can be reduced to that of finding an Euler tour. On the other hand, if G is strongly connected but not symmetric, then every edge in G is contained at least once, but perhaps more than once, in a RCP tour. Thus, the RCP problem on a graph G replicates each edge so that the resulting graph is a symmetric graph such that the sum of the costs of the replicated edges is minimized, and finds an Euler tour of the resulting symmetric graph; hence, RCP tour of the original graph G[4].

In[4], the use of multiple minimum-length UIO(MUIO) sequence of each state is proposed. A key observation is that there may exist several minimum-length UIO sequences for a given state and a judicious choice of UIO sequences for each edge can reduce the length of the overall test sequence.

In[8], we propose a approache for automatically generating conformance test sequences of communication protocols by means of MUIO and Shortest Path(MUSP). The approach is based on MUIO approach proposed by Shen[3] and uses the shortest paths to minimize the number of edges augmented for a graph to be symmetric. As a result, we directly derive a symmetric graph from a FSM graph, as opposed to the previous approach[3]. But this technique, still, has an open issue that one MUIO sequence assignment may lead to two more edges of unit cost being replicated to form G* while an optimal assignment may lead to the replication of a single edge of high cost[3]. To solve this problem, we propose a approach using Multiple Unique State Signature (MUSS) instead of MUIO sequence.

This paper is organized as follows : Section 2 reviews the RCP/MUIO approach and the MUSP approach. Section 3 proposes new technique which use the MUSS to minimize the length of the test sequence. Section 4 describes the simulation result. Finally, in Section 5, conclusions are given.

II. Previous Works on the UIO-Method

1. A Method Using MUIO

A protocol can be specified as a deterministic finite state machine(FSM). A FSM represents a directed graph G=(V, E),

Manuscript received August 30, 1996; accepted May 30, 1997.
The Authors are with ETRI, Yusong P.O. BOX 106, Taejeon, Korea.

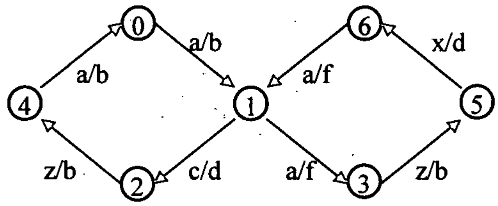

Fig. 1. A graph representation of a FSM.

where V is a finite, non-empty set of vertices and E is a set of edges. The vertices of G are the states of a FSM. Each edge is labeled as *a/o*, where *a* and *o* respectively, represent an input and an output operation. Each edge of FSM represented by a tuple (V_i, V_j, a/o). The cost associated with each edge is the time taken to realize the corresponding transition in the FSM. An example of a graph representation of a FSM is shown in Fig. 1.

Suppose that an edge (V_i, V_j:a/o) is to be tested. First, the FSM has to be put into the state corresponding to vertex V_i. Then, the input operation *a* is applied to the FSM and the output *o* is checked. If the output generated by the FSM is not *o*, then the test fails. If the output is correct, the new state of the FSM is identified in the third step.

Aho and Dahbura[2] proposed a UIO sequence to verify that the protocol implementation is in an expected state. This technique is based on RCP/UIO, as briefly outlined here.

1) Construct a directed graph $G' \equiv \{V', E'\}$ from G, where $V' \equiv V$ and $E \equiv E \cup E_C$, $E_C = \{(V_i, V_k; a_i/a_m \cdot UIO_j) : (V_i, V_j; a_i/a_m) \in E$, and $tail(UIO_j) = V_k\}$
2) Construct a directed graph G* from the test graph G' by duplicating some edge of G, such that the total cost of edges in G* is minimum and the in-degree of each vertex $V_i \in G^*$ is equal to its out-degree.
3) Find an Euler Tour of G*.

The UIO-method assumes a minimal, strongly connected, and completely specified machine. It is assumed that all graphs given here satisfy these assumptions.

Shen et al.[4] derived the multiple UIO sequences for each state in the specified FSM. A key observation is that there may exist several minimum-length UIO sequences for a given state. Therefore a judicious choice of UIO sequences for each edge could reduce the length of the overall test sequence. The multiple UIO sequence assignment procedure finds G' such that $\Delta(G') = \sum_{i=0}^{n-1} | d_{in}^{E_c}(V_i) - d_{out}^{E_c}(V_i) |$ is minimized, where $d_{in}^{E_c}(V_i)$ and $d_{out}^{E_c}(V_i)$ denote the in-degree and out-degree of vertex V_i in graph G', respectively.

For example, MUIO sequences of the FSM of the Fig. 1 are given in Table 1.

The results of the MUIO sequence assignment using the UIO sequences of Table 1 are as follows: UIO_0^3, UIO_1^2, UIO_2^0, UIO_3^6, UIO_4^1, UIO_5^6, and UIO_6^2, where UIO_i^j is a minimum-length UIO sequence of vertex V_i with $tail(UIO_i^j) = V_j$. The G' of the graph of Fig. 1 is shown in Fig. 2. The value of $\Delta(G')$ equals to 6.

Table 1. The Multiple UIO's for the FSM shown in Fig. 1.

Head State	MUIO sequences	Tail State
V_0	a/b, a/f a/b, c/d	V_3 V_2
V_1	c/d	V_2
V_2	z/b, a/b	V_0
V_3	z/b, x/d	V_6
V_4	a/b, a/b	V_1
V_5	x/d	V_6
V_6	a/f, a/f a/f, c/d	V_3 V_2

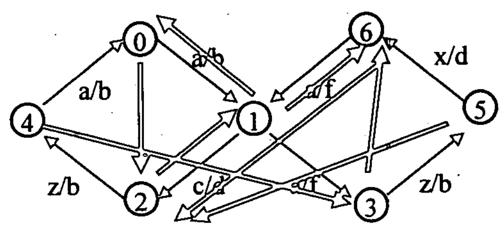

Fig. 2. The graph for the graph shown in Fig. 1.
(Bold edges represent E_c and fine edges represent E)

Table 2. A test sequence for the FSM shown in Fig. 1(dash line represents a test segment.).

<u>a/b,c/d,</u> <u>z/b,a/b,a/b,</u> <u>a/f,z/b,x/d,</u> <u>a/f,c/d,</u> (V_2,V_4), <u>a/b,a/b,a/f,</u> (V_3,V_5), <u>x/d,a/f,c/d,</u> (V_2,V_4), (V_4,V_0), (V_0,V_1), (V_1,V_3), <u>z/b,x/d,</u> (V_6,V_1), <u>c/d,z/b,a/b</u>

Table 3. Another test sequence for the FSM shown in Fig. 1.

<u>a/b,c/d,</u> <u>z/b,a/b,a/b,</u> <u>a/f,z/b,x/d,</u> <u>a/f,c/d,</u> (V_2,V_4), <u>a/b,a/b,a/f,</u> (V_3,V_5), <u>x/d,a/f,c/d,</u> <u>z/b,x/d,</u> (V_6,V_1), <u>c/d,z/b,a/b</u>

To find G* from the G' in Fig. 2, seven edges are added to G'(two edges at (V_2,V_4), one edge at (V_4,V_0), (V_0,V_1), (V_1,V_3), (V_3,V_5), and (V_6,V_1)). The resulting Euler tour consisting of 28 input/output pairs is given in Table 2.

Suppose that we have another test-graph G'' with edge (V_5,V_2) instead of edge(V_5,V_3) (use UIO_6^2 instead of UIO_6^3) in G'. The value of $\Delta(G'')$ equals to 6. But only three edges((V_2,V_4), (V_3, V_5), and (V_6,V_1)) are added for G'' to be symmetric. The resulting Euler tour is given in Table 3; the cost of the new test sequence is only 24, yielding a reduction of 11% over the sequence given in Table 2.

2. A Method Using MUIO and Shortest Paths

In the previous section, it was seen that the assignment of edges to UIO sequences which minimize the $\Delta(G')$ may not minimize the length of the tour. Since there is no guarantee on the cost of the set of edges which are augmented to produce G* from G'. In this paper, we propose the use of shortest path to minimize the number of augmented edges.

Let the vertices V_K and V_l need some outgoing edges and some incoming edges for producing G* from G', respectively. If there is no edges $(V_k, V_l)\in E$, then G* is made by duplicating the edges included in the shortest path from V_k to V_l. Thus, the number of edges augmented to G' for making the G' to be symmetric are minimized.

Given G, let $G_N=\{V_N, E_N\}$ be a directed graph such that $V_N\equiv\{S, T\}\cup V_X\cup V_Y$, where $V_X=\{X_0, X_1,\cdots X_{n-1}\}$and $V_Y=\{Y_0, Y_1,\cdots Y_{n-1}\}$ and $E_N\equiv E_S\cup E_T\cup E^{\wedge}\cup E_{SH}$, where $E_S=\{(S, X_i)\in V_X\}$, $E_T=\{(Y_j, T);Y_j\in V_Y\}$, $E^{\wedge}=\{(X_i, Y_j)$:there exists $UIO_i^j\}$, and $E_{SH}=\{(Y_i, Y_j);Y_i, Y_j\in V_Y\}$. Let each edge $(S, X_i)\in E_S$ have zero cost and $d_{in}^E(V_i)$ capability; let each edge $(Y_j, T)\in E_T$ have zero cost and $d_{out}^E(V_j)$ capability; let edge $(X_i, Y_j)\in E^{\wedge}$ have β_j(the length of UIO_i^j) cost and infinite capability; and let each edge $(Y_i, Y_j)\in E_{SH}$ have α_{ij} (the length of the shortest path from V_i to V_j in G) cost and infinite capability. Then a flow F_N on G_N is a function satisfying the following conditions:

$$\text{for each vertex } X_i\in V_X,\ d_{in}^E(V_i)=\sum_{(X_i,Y_j)\in E^{\wedge}}F_N(X_i, Y_j) \quad (1)$$

for each vertex $Y_j\in V_Y$,

$$d_{out}^E(Y_j)+\sum_{(Y_j,Y_i)\in E_{SH}}F_N(Y_j, Y_i)=\sum_{(X_k,Y_j)\in E^{\wedge}}F_N(X_k, Y_j) = \sum_{(Y_k,Y_j)\in E_{SH}}F_N(Y_k, Y_j) \quad (2)$$

The cost of the flow F_N is :

$$C(F_N)=\sum\sum_{(Y_i,Y_j)\in E^{\wedge}}\beta_{ij}F_N(X_i, Y_j) +\sum\sum_{(Y_i,Y_j)\in E_{SH}}\alpha_{ij}F_N(Y_i, Y_j)$$

Given a minimum-cost maximum flow f_N on G_N, if we assign exactly one UIO_j^i sequence to each incoming edge $(V_i, V_j)\in E$, so each $UIO_j^i\in MUIO_j$ is used exactly $f_N(X_j, Y_i)$ times, then we can construct G'. If we replicate some edges $(V_i, V_j)\in E$ exactly $f_N(Y_i, Y_j)$ times, we obtain G*. Note that, since there exist edges of infinite capacity from each $X_i\in V_X$ to some $V_j\in V_Y$, the equation (1) guarantees that each edge in G is assigned a UIO sequence.

Theorem 1 : If f_N is a minimum-cost maximum flow in G_N and G_N^* is constructed from the f_N, then the corresponding assignment of UIO to edges of G minimizes the number of edges replicated for G' to be symmetric.

Proof : This proof is given in[8].

Table 4. A part of the Multiple USSs for the FSM shown in Fig. 1.

Head State	MUSS Sequences	Tail State
V_0	a/b, c/d, z/b, a/b	V_0
	a/b, c/d, z/b, a/b, a/b	V_1
	a/b, c/d	V_2
	a/b, a/f	V_3
	a/b, c/d, z/b	V_4
	a/b, a/f, z/b	V_5
	a/b, a/f, z/b, x/b	V_6
V_1	c/d, z/b, a/b	V_0
	c/d, z/b, a/b, a/b	V_1
	c/d	V_2
	c/d, z/b, a/b, a/b, a/f	V_3
	c/d, z/b	V_4
	a/f, z/b	V_5
	a/f, z/b, x/b	V_6
⋮	⋮	⋮

III. Proposed Method Using MUSS

Note that flows f_N on G_N reduces the cost of the set of edges which are augmented to produce G* from G' and directly, derive G* from a FSM graph. The multiple UIO sequence assignment procedure only derives G' from a FSM graph. One open issue is that one MUIO sequence assignment may lead to two more edges of unit cost being replicated to form G* while an "optimal" assignment may lead to the replication of a single edge of high cost[4]. To solve this problem, let introduce $MUSS=\{\{USS_0^0,\cdots USS_0^{n-1}\},\cdots\{USS_{n-1}^0,\cdots USS_{n-1}^{n-1}\}\}$, where USS_i^j represents the minimum-length Unique State Signature(USS) with the tail state V_j for a given state V_i and the length of $USS_i^{j_1}$ may not equal to that of $USS_i^{j_2}$ for any $j_1\neq j_2$ (In case of MUIO, the length of $UIO_i^{j_1}$ equals to that of $UIO_i^{j_2}$).

For example, a part of MUSS sequence of the FSM of Fig. 1 is given in Table 4.

Given G, let $G_L=\{V_L, E_L\}$ such that $V_L\equiv\{S, T\}\cup V_X\cup V_Y$ and $E_L\equiv E_S\cup E_T, \cup E_L^A$, where $E_L^A=\{(X_i, Y_j);\ X_i\in V_X \text{ and } Y_j\in V_Y\}$. Each edge $(X_i, Y_j)\in E_L^A$ has cost γ_{ij}(the length of US_i^j) and infinite capability. A flow f_L on G_L is a function satisfying the following conditions:

$$\text{For } X_i\in V_X,\ d_{in}^E(V_i)=\sum_{(X_i,Y_j)\in E_L^A}F_L(X_i, Y_j) \quad (3)$$

$$\text{For } Y_j\in V_Y,\ d_{out}^E(V_j)=\sum_{(X_i,Y_j)\in E_L^A}F_L(X_i, Y_j) \quad (4)$$

The cost of the flow F_L is $C(F_L)=\sum\sum_{(X_i,Y_j)\in E_L}\gamma_{ij}F_L(X_i, Y_j)$.

Theorem 2 : If f_N and f_L are a minimum-cost maximum flow in G_N and G_L, respectively, then $C(f_L)\leq C(f_N)$.

Table 5. The test sequence generated using MUSS for the FSM shown in Fig. 1.

<u>a/b,c/d,</u> <u>z/b,a/b,a/b,</u> <u>a/f,z/b,x/d,</u> <u>a/f,a/f,z/b,</u> <u>x/d,a/f,a/f,z/b,</u> <u>a/b,a/b,a/f,</u> <u>z/b,x/d,a/f,</u> <u>c/d,z/b,a/b</u>

Proof : Let the length of USS_i^j be δ_i^j for each $USS_i^j \in MUIO_i$ and the length of USS_i^j be ε_i^j for $USS_i^j \notin MUIO_i$. Suppose that we obtain f_N flows on any G_N and there exist vertices Y_k and Y_l needed to an incoming edge and an outgoing edge, respectively. The cost of G_N is $C(f_N) = \sum \sum_{(X_i, Y_j)\in E'} \beta_{ij} f_N(X_i, Y_j) + \alpha_{lk}$. To produce G_L, let us assign flows f_N to edges in G. In order that the flows satisfy the equation (3) and (4), any assigned edge $USS_m^l \in MUIO_m$ must be extracted and any other edge $USS_m^k \notin MUIO_m$ must be assigned.
The cost of G_L is $C(f_L) = \sum \sum_{(X_i, Y_j)\in E'} \beta_{ij} f_N(X_i, Y_j) - \delta_m^l + \varepsilon_m^k$.
Note that $\delta_m^l = \beta_{ml}$ for all $USS_m^l \in MUIO_m$ and $\varepsilon_m^k = \min[\min_n \{\delta_m^n + \alpha_{nk}\}, \varepsilon_m^k]$ for all $USS_m^k \notin MUIO_m$. From these facts, $C(f_L) - C(f_N) = \varepsilon_m^k - \delta_m^l - \alpha_{lk} = \varepsilon_m^{k-}(\delta_m^l + \alpha_{lk}) \le 0$. □

Theorem 3 : If f_L is the minimum-cost maximum flow on G_L and G_L^* is constructed from the f_L, then the corresponding assignment of USS to edges of G minimizes the number of edges augmented to produce G* from a FSM graph.

Proof : The equation (3) guarantees that each edge in G_L is assigned a USS sequence and the equation (4) can be rewritten as $d_{out}^{E_C}(V_j) = d_{in}^{E_C}(V_j)$. Therefore, $\sum \sum_{(X_i, Y_j)\in E_L'} \gamma_{ij} F_L(X_i, Y_j)$ means the total number of edges which must be added to obtain a G* from a FSM graph. □

The flows f_L using MUSS given in Table 4 for the FSM shown in Fig. 1. are as follows: $f_L(X_0, Y_3)=1$, $f_L(X_1, Y_2)=1$, $f_L(X_1, Y_5)=1$, $f_L(X_2, Y_0)=1$, $f_L(X_3, Y_6)=1$, $f_L(X_4, Y_1)=1$, $f_L(X_5, Y_1)=1$, and $f_L(X_6, Y_4)=1$. The resulting test sequence is shown in Table 5. The total test sequence contains 21 transitions, saving of 3 transitions over the sequence generated using the MUIO.

Ⅳ. Simulation Results

The procedure of generating MUIO/MUSS sequences per state, constructing the graph G_N/G_L, computing minimum-cost maximum flow on G_N/G_L, and assigning a state signature to edges accordingly, was performed on a number of FSM specifications and yielded favorable results, as shown in Table 6. Randomly generated FSMs have been studied as test cases. Table 6 indicates that the technique using MUSP saves the cost 4~28% and 2~21% over the MUIO and the MUSP approach, respectively. We know that the value $|E_C|$ of of MUSS is larger than the one of MUIO and MUSP, but the total length of the test sequence is shorter.

Table 6. The length of tours generated using MUIO, MUSP, and MUSS for some sample FSMs.

FSM	|V|	|E|	|I|	|O|	E_C (MUIO, MUSP)	E_C (MUSS)	Total Cost (MUIO)	Total Cost (MUSP)	Total Cost (MUSS)
FSM.1	7	20	5	5	47	55	76	70	55
FSM.2	10	43	10	10	86	94	105	102	94
FSM.3	10	49	10	10	103	110	114	112	110
FSM.4	10	38	10	5	80	89	105	94	89
FSM.5	10	43	5	5	97	108	129	117	108

Ⅴ. Conclusions

Test Sequence generation for conformance testing has been widely advocated for ensuring that protocol implementations are consistent with their specifications[3]. Several approaches have been developed for protocol conformance testing[1-6]. The test sequence is generated by an approximation algorithm which guarantees that each transition of the specified FSM is traversed at least once.

In this paper, we propose another approach using Multiple Unique State Signature(MUSS) instead of MUIO sequence to solve a open issue that we propose another approach using Multiple Unique State Signature(MUSS) instead of MUIO sequence. As a result, the number of edges augmented to produce a G* from a graph G is minimized.

Randomly generated FSMs have been studied as test cases. The proposed approach using MUSS saves the cost 4~28% over the MUIO approach and the cost 2~21% over the MUSP.

In[1], it was shown that if G' is a weakly connected graph, while NP-complete in general, the RCP has a polynomial-time solution. It is possible that this condition is not met when the MUSP method and the MUSS method are used. If G' is not weakly connected, then various simple heuristics can be used[3, 6]. The cost of the resulting test sequence will usually slightly increased.

References

[1] A. Aho, A. T. Dahbura, D. Lee, and U. Uyar,(1991) "An Optimization Technique for Protocol Conformance Test Generation Based on UIO sequence and Rural Chinese Postman Tour", IEEE Transaction on Communications, Vol. 39, No. 11, pp. 1604-1615, 1991.

[2] K. K. Sabnani, and A. T. Dahbura, "A Protocol Test Generation Procedure", Computer Networks and ISDN Systems, Vol. 15, No. 4, pp. 285-297, 1988.

[3] Y. N. Shen, F. Lombardi, and A. T. Dahbura, "Protocol

Conformance Testing Using Multiple UIO Sequence", IEEE Transaction on Communications, Vol. 8, pp. 1282-1287, 1992.

[4] M. U. Uyar, and A. T. Dahbura, "Optimal Test Sequence Generation Protocols : The Chinese Postman Algorithm Applied to Q.931", Proceedings of the IEEE Global Communication Conference, Vol. 1, pp. 68-72, 1986.

[5] D. Sidhu and T. K. Leung, "Formal methods for protocol testing: A detailed study", IEEE Transaction Software Engineering, Vol. 14, No. 4, pp. 413-426, 1989.

[6] Wen-Huei Chen and Hasan Ural, "Synchronizable Test Sequences Based on multiple UIIO sequences", IEEE/ACM Transactions on Networking, Vol. 3, No. 2, pp. 152-157, 1995.

[7] OSI Conformance Testing Methodology and Framework-Part 1-5.

[8] Yoon-Hee, Jung and Beom-Kee, Hong, "The Test Sequence Generation Using MUIO and Shortest Paths", The Journal of the Korean Institute of Communication Sciences, Vol. 21, No. 5, pp. 1193-1199, 1996.

Yoon-Hee Jung received the B.S. degree in Industrial Engineering from HanYang University in 1990, and M.S. degree from KAIST(Korea Advanced Institute of Science and Technology) in 1992. His current research staff of ETRI(Electronics and Telecommunications Research Institute).

Beom-Kee Hong received the B.S. degree in Computer Science from Hong Ik University in 1982, and M.S. degree in 1984, and Ph.D. degree in Computer Engineering, ChungBuk National University. His current research staff of ETRI(Electronics and Telecommunications Research Institute), and Managing Director of KOWRI(Korea Wireless Research Institute).