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Availability Analysis of Electronic Flight Instrument System based on Dynamic Fault Tree*

1st DONG Haiyong, 3rd WANG Guoqing, 4th ZHAI Zhengjun, and 5th LU Yanhong
School of Computer Science and Engineering
Northwestern Polytechnical University
Xi' an, PR China
donghaiyong@mail.nwpu.edu.cn

2nd GU Qingfan
Civil Aviation Department
China National Aeronautical Radio Electronics Research Institute
Shanghai, PR China
gu_qingfan@careri.com

***Abstract*—As a high availability product, Electronic Flight Instrument System (EFIS) has very complicated redundancy structures to fulfill high safety integrity requirement. This paper presents a comprehensive study on the availability analysis for EFIS by using Dynamic Fault Tree (DFT) approach based on Markov chain with modularization method. The static fault sub-tree is solved by Binary Decision Diagram (BDD) and the dynamic fault sub-tree is solved by Markov chain. A novel Markov chain expression is utilized to avoid state explosion of dynamic fault sub-tree. Besides, Minimal Cut Sequence Set (MCSS) are generated. At last, Monte Carlo simulation is carried out to verify the theoretical results.**

Keywords—availability analysis; dynamic fault tree; electronic flight instrument system; markov chain; minimal cut sequence set

I. Introduction

With the development of the technology, reliability of complex system has been improved significantly, especially in aviation, nuclear industry, high-speed rail and other safety-critical system[1]. Civil aircraft always requires high reliability, and the availability is an important quantitative basis for reliability assessment. Moreover the availability of its devices and avionics should be certified based on applicable standards of SAE ARP 4761 and other current standards[2][3] to guarantee the required high reliability. Modern Electronic Flight Instrument System (EFIS) is a flight deck instrument display system that provides primary flight display and navigation display function electronically. To improve the availability of EFIS, redundancy technique is utilized. What's more, modern EFIS system exits common shared component to reduce weight, so EFIS is a safety-critical system with sequence-dependent failure behavior. In other words, the failure order of its components in EFIS affects the outcome state.

For the last few decades, many scholars have carried out a series of different methods to assess the reliability of safety-critical system. By August 2016, 847 safety methods have been proposed to study almost every aspect of safety assessment[4]. In the domain of avionics, many researchers utilize Fault Tree Analysis (FTA), Dependence Diagram (DD), Markov Analysis (MA) and other methods to assess the reliability. Many researchers work on the reliability assessment of avionics hardware and software system, and they proposed many safety methods on qualitative and quantitative evaluation[5,6,7,8]. However, few studies have focused on the reliability assessment of EFIS. Moir constructed a model of EFIS and evaluated its availability, whereas the structure of this EFIS was simplified and modeled as a static system without taking into account sequence-dependent failure behavior[9].

FTA is one of the most popular logic and probabilistic methods used in system reliability assessment[10]. Initially, FTA is designed by Bell Telephone Laboratories to assess the risk and reliability of US missile programs in the early 1960s. AND gate and OR gate are basic gates and they are used frequently. Along with the increasing complexity of the to-be-analyzed system, more and more gates are designed to simplify the expression of FTA, and the qualitative and quantitative evaluation become more complex. Throughout the develop history of FTA, new gates are always designed for special occasions. However, without these new gates (e.g. hot spare gate, priority and gate), the fault-tolerant system is more difficult to understand and evaluate[11]. In order to express the sequence-dependent behavior and common-cause failures of fault-tolerant systems, Dynamic Fault Tree (DFT) methodology was proposed by Dugan. Furthermore, DFT always integrate Markov chain[12], Bayesian model[13], Petri net[14], Go-Flow methodology[15], Monte Carlo simulation[16], and other well-established theories to assess the reliability of dynamic system. Since Markov chain can model the sequence-dependent behavior easily, it has been widely used to assess the reliability of fault-tolerant systems[17]. However, Markov chain has the disadvantage of being large and cumbersome. In other words, with the increasing number of basic elements, state space explosion problem occurs[18]. In order to reduce state space and minimize the computational time, Dugan proposed an optimized modularization method which divide the dynamic fault tree into static and dynamic fault sub-trees[19]. Static fault sub-tress can be used to deal with Binary decision diagram (BDD), which is an efficient and precise approach in quantifying probabilities based on structure function[20], while Markov chain is used to deal with the dynamic fault sub-tree,

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so that the availability of the whole dynamic fault tree could be calculated.

On the basis of the above discussions, we attempt to articulate the typical structure, failure modes, and functional dependencies of EFIS using dynamic fault tree. We divide the dynamic fault tree into static and dynamic fault sub-trees assessed by BDD method and Markov chain. A novel Markov chain is presented to avoid state space explosion problem. Then the sequence cut set of dynamic fault sub-tree are given, as well as the failure rate of each sequence cut. In this way, we find some potential rules. Lastly, 10 billion times Monte Carlo simulation is carried out to verify the theoretical availability of EFIS.

This paper aims for providing an integrated process to assess the availability of EFIS, as well as making Markov chain more efficient. The remainder of this paper is organized as follows. In Section II, a brief overview of EFIS and its typical structure and failure modes are given, and the dynamic fault tree is modeled. In Section III, availability of EFIS is evaluated and results are verified. In the final section, the results of the research and future research recommendations are presented.

II. CONSTRUCTION OF EFIS DYNAMIC FAULT TREE

EFIS displays critical flight data (attitude, altitude, altimeter, airspeed, etc.) to crew members by primary flight display (PFD) and navigation display (ND) functions. Figure 1 shows structure of a typical EFIS[9, 21]. There are 3 symbol generators (SG) which obtain the critical flight data from the pair of sensors and output image data on to 4 display units (DUs) in the flight deck. Every SG can produce both PFD and ND data simultaneously. Every DU gets its display data from a normal or an alternate SG source. Normally, SG#1 outputs the image on PFD#1 and ND#1 for the captain's displays, SG#2 outputs the image on PFD#2 and ND#2 for the first officer's displays. And SG#3 is a hot spare symbol generator of both SG#1 and SG#2, and it is able to substitute SG#1 or SG#2 when they fail. Select switch (Sel SW) is used to select one DU to be a integrated PFD&ND display in the event of another DU in the same group fails. In addition, an integrated standby instrument system (ISIS) is required to be applied independently to show critical flight data (attitude, airspeed and altitude) when the event of complete failure of the main display system occurs.

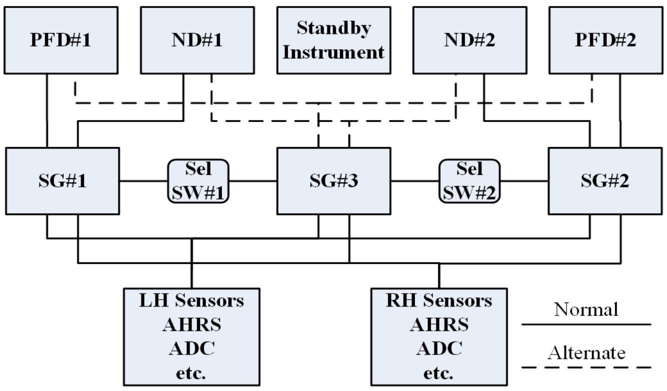

Fig. 1. Typical EFIS structure

The US and European Aviation Certification Authorities have classified the failures into four degrees (Minor, Major, Hazardous and Catastrophic) according to their severity[2][3]. Moir defined "the total loss of critical flight data from the flight deck" as a catastrophic failure and its probability should less than 10^{-9} per flight hour[9].

The structure of EFIS is fault-tolerant and its strategies of failure management are shown below.

- If a DU fails, the select switch will be rotated by the crew to select another available DU in the same side, and then the normal DU will be an integrated PFD&ND display to show all required critical flight data.
- If a SG fails, then the hot spare (SG#3) will take over the invalid SG and output the critical flight data on to the DUs. In this way, the outputs of SG#3 keep independent.
- If the main display suit fails, the crew members will start applying the ISIS.

Based on the structure analysis of EFIS, we find that (1) EFIS contains 2 independent subsystems, ISIS and main display, which are shown as "and" gate, so only after both 2 subsystems fail, then the EFIS is announced fault. (2) Main display subsystem consists of data source module, symbol generators module, and display units module, which are shown as "or" gate, meaning that failure of either module announced main display subsystem fault. (3) Data source module contains 4 sensors, while critical flight data contains attitude, airspeed and altitude, among them attitude is from Attitude and Heading Reference System (AHRS) and other data are from Air Data Computer (ADC), so this module can be modeled as two independent data source parts, which are shown as "or" gate, meaning that data source module fault is announced when either part fails. (4) Since both types data sensors are duplex and segregated, which are shown as "and" gate, only after both 2 same sensors fails, then the data source part fault is announced respectively. (5) Display units module consists of 4 independent display units, which are shown as "and" gate and every display unit can work as a composite PFD/ND display, so display units module is announced fault after all 4 display units are failure. (6) Since PFD#1 and ND#1 source from SG#1 or SG#3, so failures of both SG#1 and SG#3 could lead to PFD#1 and ND#1 unusable. Similarly, failures of both SG#2 and SG#3 could lead to PFD#2 and ND#2 unusable. The failure mode can be modeled by the "functional dependency" (FDEP) gate. (7) As SG#3 is the hot spare equipment of SG#1 and SG#2, the failure mode can be modeled by the "hot spare" (HSP) gate. (8) On the occasion of corresponding select switch fails before a PFD or ND fails, the other normal display unit in the same side cannot convert into a composite PFD/ND display and is assumed as unusable. This failure mode can be modeled by the "Priority and" (PAND) gate and FDEP gate. Based on the above analysis, the total loss of critical flight data from flight deck is adopt as the top event, then the DFT of EFIS is established in Figure 2.

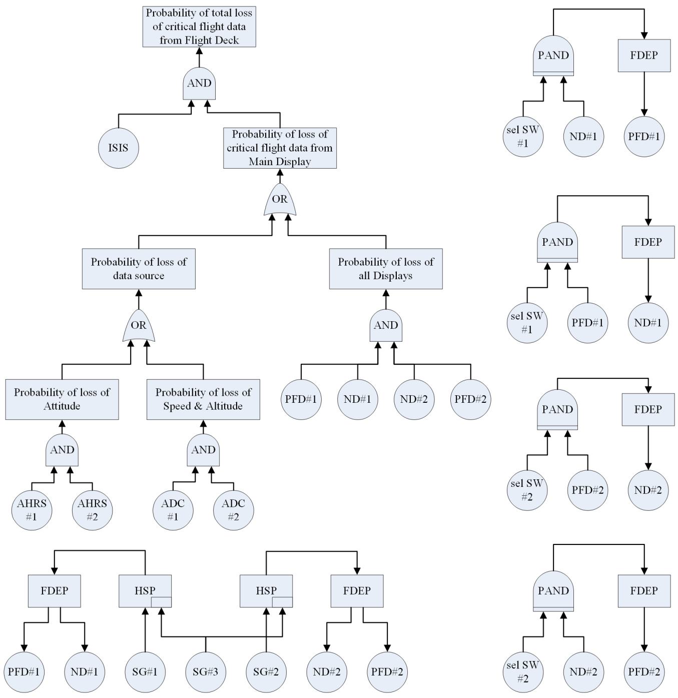

Fig. 2. Dynamic Fault Tree of EFIS

III. AVAILABILITY ANALYSIS OF EFIS

According to the above process of constructing the dynamic fault tree of EFIS system, there are many types of dynamic failure modes in the dynamic fault tree. In this paper, we adopt modularization method to divide the dynamic fault tree into static and dynamic fault sub-trees. BDD is used to deal with the static fault sub-tress, and Markov chain is applied to deal with the dynamic fault sub-tree. Then the availability of the whole dynamic fault tree is calculated. Lastly, we use Monte Carlo simulation to verify the theoretical result of Markov chain.

A. Basic Event Failure

There are 14 components/subsystems within the EFIS shown in Figure 1. All of these components are independent, in other words, the single failure or combination failures of one or some components cannot affect the structure failure of other components. To further simplify the model, there are five general assumptions listed below[7,9,11].

- Faults are modeled as statistically independent distributed events.
- The Failure rate of a component is a constant.
- Fault occurs instantaneously, and no more than one failure event occurs in a minimum time slice.
- The system and its parts can only be in the state of normal or failure.
- The system and its parts cannot be repaired while in use.

We quote the failure rate of these components per flight hour from the book written by Malcolm Jukes[21], while these

TABLE I. FAILURE RATE OF COMPONENTS IN EFIS

Component	MTBF	Failure Rate per hour
Integrated Standby Instrument System (ISIS)	5000 hrs	2.0×10^{-4}
Attitude and Heading Reference System (AHRS)	15000 hrs	6.67×10^{-5}
Air Data Computer (ADC)	20000 hrs	5.0×10^{-5}
Display Unit (DU)	7500 hrs	1.33×10^{-4}
Symbol Generator (SG)	10000 hrs	1.0×10^{-4}
Select Switch (Sel SW)	30000 hrs	3.33×10^{-5}

figures do not represent the accurate failure probabilities of actual components. The Mean Time between Failure (MTBF) and failure rate per flight hour of these types of components are shown in Table I.

Note that PFD and ND have the same failure rate with DU. In Figure 2, the top event is a functional failure rate obviously. While these 14 components/subsystems may fail due to its own structure failure or other reasons, for example, the failures of SG#1 and SG#3 cannot lead to the structure failure of PFD#1, but it leads to the functional failure of PFD#1. Thus, the figures in Table 1 are the own structure failure rate of these components.

B. Analysis of Static Fault Sub-tree based on BDD

As shown in Figure 1, EFIS system consists of 2 subsystems: Main Display and the ISIS. Unless both of these 2 subsystems fail, then the top event occurs. We can calculate the availability based on Binary Decision Diagram (BDD) method. The BDD method not only provides an accurate calculation of the top event probability, but also supports basic event validation in a specific minimal cut set which is necessary to cause the top event. BDD contains 2 types of end nodes, 0 and 1 respectively. 0 represents normal state and 1 represents the state of failure. Figure 3 shows the BDD diagram of EFIS.

The structure function of the dynamic fault tree for EFIS can be obtained as follows.

$$\Phi(X_{EFIS}) = X_{ISIS} \cap X_{MainDisplay} \tag{1}$$

So $\Pr[\Phi(X_{EFIS})]$ is the availability of the top event, and $\Pr[\Phi(X_{EFIS}) = 1]$ denotes the probability of the top event.

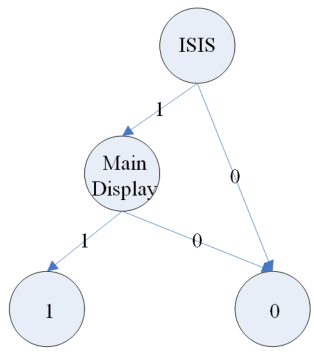

Fig. 3. BDD of EFIS fault tree

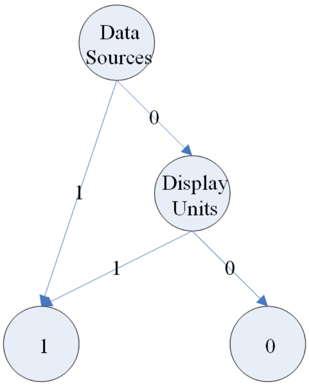

Fig. 4. BDD of Main Display fault sub-tree

In the same way, the BDD of Main Display is obtained and it is shown in Figure 4.

The structure function of the dynamic fault sub-tree for Main Display can be obtained as follows.

$$\Phi(X_{MainDisplay}) = X_{DataSources} \cup X_{DisplayUnits} \tag{2}$$

Since the fault sub-tree of Data Sources is static fault tree which only consists of “and” and “or” gate, so the BDD of Data Sources can be obtained and it is shown in Figure 5.

The structure function of the fault sub-tree for Data Sources can be obtained as follows.

$$\Phi(X_{DataSources}) = (X_{AHRS\#1} \cap X_{AHRS\#2}) \cup (X_{ADC\#1} \cap X_{ADC\#2}) \tag{3}$$

Note that the dynamic fault sub-tree of Display Units contains some dynamic gates, so it is considered as an entirety to be deal with Markov chain in next subsection.

Based on equation (1), (2), and (3), the structure function for EFIS is obtained as shown in equation (4).

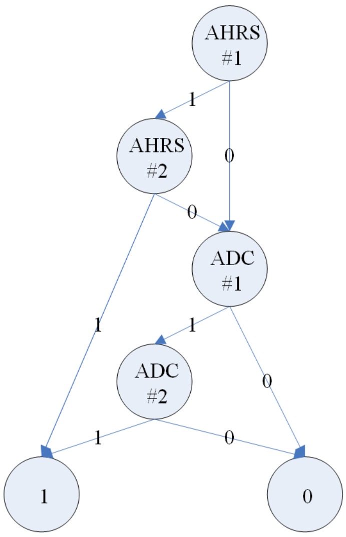

Fig. 5. BDD of Data Sources fault sub-tree

$$\begin{aligned}
&\Phi(X_{EFIS}) \\
&= X_{ISIS} \cap \left(((X_{AHRS\#1} \cap X_{AHRS\#2}) \cup (X_{ADC\#1} \cap X_{ADC\#2})) \cup X_{DisplayUnits}\right) \\
&= X_{ISIS} \cap (X_{AHRS\#1} \cap X_{AHRS\#2}) + X_{ISIS} \cap (X_{ADC\#1} \cap X_{ADC\#2}) \\
&\quad + X_{ISIS} \cap X_{DisplayUnits}
\end{aligned} \tag{4}$$

Based on the analysis above, probability of the top event is obtained as follows.

$$\begin{aligned}
&\Pr[\Phi(X_{EFIS}) = 1] \\
&= \Pr[X_{ISIS} X_{DisplayUnits} = 1] \\
&+ \Pr[X_{ISIS} \overline{X_{DisplayUnits}} X_{AHRS\#1} X_{AHRS\#2} = 1] \\
&+ \Pr[X_{ISIS} \overline{X_{DisplayUnits}}\, \overline{X_{AHRS\#1}}\, \overline{X_{AHRS\#2}} X_{ADC\#1} X_{ADC\#2} = 1]
\end{aligned} \tag{5}$$

C. Analysis of Dynamic Fault Sub-tree Based on Markov Chain

In Figure 2, the event “probability of total loss of all displays” is a dynamic fault sub-tree, including three basic dynamic fault gates: the priority AND (PAND), the functional dependency (FDEP), and the hot spare (HSP). Because this dynamic fault sub-tree consists of 9 components and the state of every component can be normal and failure, so there are 2^9=512 states from the state of Normal (all normal) to the state of Fail (all failure). What’s more, there are 9!=362880 permutations of 9 independent component failures, and every permutation may be a cut sequence. So this Markov chain is too big to express.

We find that this fault sub-tree is depended on the state of 4 display units (DUs), while the DUs can be divided into 2 independent groups, one is defined as L_DU including PFD#1 and ND#1, and another one is defined as R_DU including PFD#2 and ND#2. In this way, we can get the novel Markov chain of this fault sub-tree in Figure 6 based on the principle of transforming dynamic fault tree to Markov chain.

The event “probability of total loss of all displays” occurs on the condition of both L_DU and R_DU fail. According to the basic theory of Markov chain, the failure probability of L_DU can be derived and denoted as Pr(L_DU).

$$\begin{aligned}
&\Pr(L_DU) \\
&= \frac{\lambda_{DU} \times \lambda_{DU}}{2!} + \frac{\lambda_{DU} \times \lambda_{DU}}{2!} + \frac{\lambda_{SelSW} \times 2\lambda_{DU}}{2!} + \frac{3\lambda_{SG} \times \lambda_{SG}}{2!} \\
&= \lambda_{DU}^2 + \lambda_{SelSW}\lambda_{DU} + 3\lambda_{SG}^2/2
\end{aligned} \tag{6}$$

In the same way, the failure probability of R_DU can be derived and denoted as Pr(R_DU). However, since SG#3 is the shared component for both L_DU and R_DU, “probability of total loss of all displays” cannot be derived. Fortunately, there is no chain both consists of SG and other type of components, so “probability of total loss of all displays” can be derived approximately as Pr(DUs) by separating SG.

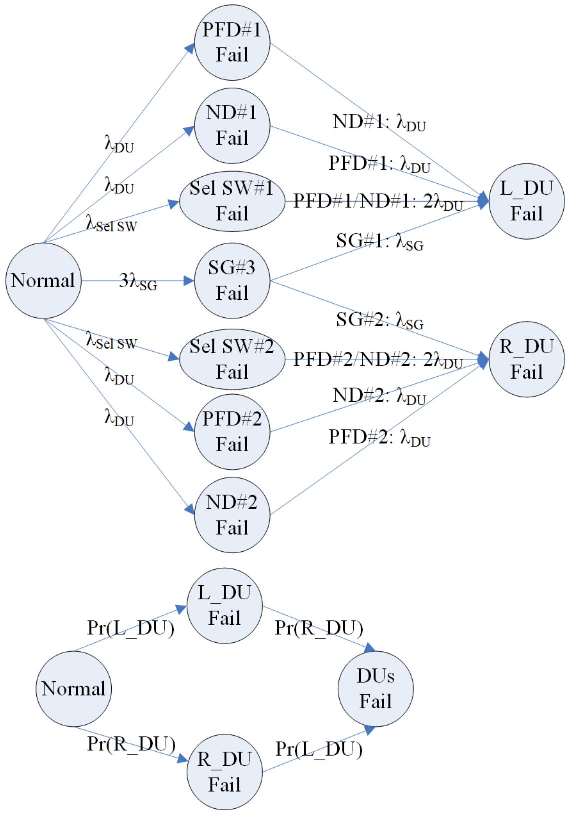

Fig. 6. Novel Markov chain of Display Units dynamic fault sub-tree

$$
\begin{aligned}
&\Pr(DUs)\\
&=\Pr(L\_DU-SG)\times\Pr(R\_DU-SG)+\Pr(DUs\_SG)\\
&=\left(\lambda_{DU}^2+\lambda_{Sel\,SW}\lambda_{DU}\right)^2+\frac{3\lambda_{SG}\times 2\lambda_{SG}\times\lambda_{SG}}{3!}\\
&=\left(\lambda_{DU}^2+\lambda_{Sel\,SW}\lambda_{DU}\right)^2+\lambda_{SG}^3
\end{aligned}
\tag{7}
$$

The symbol Pr(L_DU-SG) in equation (4) is failure probability of L_DU without the affection of SGs. Similarly Pr(R_DU-SG) is failure probability of R_DU without the affection of SG. In addition, Pr(DUs_SG) is the failure probability of all DUs by the affection of SGs.

By substituting of numerical values from Table I, we can obtain the "probability of total loss of all displays" is approximately 1.00049×10^{-12}.

Figure 6 shows a novel Markov chain that can be understand easily, and the approximate value can be obtained from equation (7). However, Minimal Cut Sequence Set (MCSS) are still difficult to derive. We utilize MATLAB to enumerate all possible Markov chain. As a result, we get 89874 cut sequences and calculate corresponding failure rates, and sort MCSS by failure rate as shown in Table II.

Noted that there are 6 cut sequences whose failure rate is larger than 10^{-13}, which make the most contribution to the top event of dynamic fault sub-tree, and these 6 sequences are full array of SG#1, SG#2, and SG#3. In addition, we accumulate all

TABLE II. FAILURE RATES OF MINIMAL CUT SEQUENCE SET OF DYNAMIC FAULT SUB-TREE IN EFIS.

No.	Failure Rate	Cut Sequence
1	1.66667×10^{-12}	SG#1, SG#2, SG#3
2	1.66667×10^{-12}	SG#1, SG#3, SG#2
3	1.66667×10^{-12}	SG#2, SG#1, SG#3
4	1.66667×10^{-12}	SG#2, SG#3, SG#1
5	1.66667×10^{-12}	SG#3, SG#2, SG#1
6	1.66667×10^{-12}	SG#3, SG#1, SG#2
7	1.30375×10^{-17}	PFD#1, ND#1, ND#2, PFD#2
…	…	…
89874	6.47028×10^{-37}	Sel SW#2, SG#3, PFD#2, PFD#1, Sel SW#1, SG#2, ND#2, SG#1

failure rates of MCSS and get the "probability of total loss of all displays" is 1.00160×10^{-12}, which is slightly larger than the result in equation (7). We find that deviation between these two failure probabilities is derived from that SGs should not be separated absolutely. Though the deviation is less than 0.12%, we adopt the larger calculate result (1.00160×10^{-12}) in follow-up section to conform to the airworthiness reliability standard.

By substituting above numerical values for equation (5), we can get the "loss probability of critical flight data on the main displays" is 6.94989×10^{-9} for one flight hour, which meets the safety requirement. Furthermore, the probability of top event is 1.38998×10^{-12}, which meets the safety requirement.

D. Validation Based on Monte Carlo Simulation

Monte Carlo method is able to obtain numerical probability results by repeating random sampling, which can be implemented by computer program. Since the loss probability of critical flight data on the main displays is small, we should simulate enough times. What's more, as a flight time can be 3 hours for domestic airplane or 15 hours for international airplane, we calculate the theoretical failure rate of Dynamic Sub-tree, Main Displays, and whole EFIS at different flight time. Then we simulate the flight time of 1 hour, 3hours, and 15 hours for 10,000,000,000 times to verify the theoretical results based on DFT. Theoretical failure rates and results of Monte Carlo simulation of subsystem and whole system for different flight time are shown in Table III.

Noted that there are 3 zeros during Monte Carlo simulation, and all their theoretical failure rates are less than 1. There is 1 one for whole EFIS of 3 hours, whose theoretical failure rate is less than 1 as well. Other result values of Monte Carlo simulation also approximately equal to the theoretical failure rate. In a word, Monte Carlo simulations verify theoretical failure rates are correct.

TABLE III. COMPARISON BETWEEN THEORETICAL RESULTS AND MONTE CARLO SIMULATION

System name	Theoretical Failure Rate (10^{-10})			Monte Carlo Simulation (times per 10^{10})		
	1 hour	*3 hours*	*15 hours*	*1 hour*	*3 hours*	*15 hours*
Dynamic Sub-tree	0.01002	0.27130	34.5637	0	0	30
Main Displays	69.4989	625.671	15669.6	64	641	15839
EFIS	0.01390	0.37540	47.0086	0	1	51

SAE ARP 4754A demands the availability of avionics system in 1 flight hour satisfy the requirement, while flight time of 3 hours and 15 hours are not required. Through the results in Table III, we find that the failure rates increase faster than time prolongs. So it is necessary to analyze the availability of avionics system for every request flight time.

IV. CONCLUSION

This paper introduces a solution for availability assessment of Electronic Flight Instrument System (EFIS), whose components have complex failure dependency. In order to analyze the availability of EFIS more accurately, this paper proposes to use dynamic fault tree based on Markov chain to model the failure of EFIS, rather than using static fault tree to model a simplified EFIS. In terms of the challenge of state space explosion problem of Markov chain, we utilize modularization method to divide the whole model into static and dynamic fault sub-tree. In addition, we separate common components to simplify the Markov chain model originality. In this way, minimal cut sequence set (MCSS) of dynamic fault sub-tree are given in this paper, and failure rate of cut sequences are given as well. At last, we simulate 10 billion times by using Monte Carlo method for different flight time, and simulation results show that the theoretical results are correct.

In the future work, we will focus on the fault propagation to aid the designation of avionics system. Furthermore, we will study the method of generating minimal cut sequence set to assess reliability of safety-critical system.

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