System Fault Diagnosis Method Based on OSDG Model

Wei Cong¹, Hongkun Yu² and Jing Liu¹

¹School of Information Engineering, Xijing University, Xi’an, 710123, China.
²Department of Continuous Education, Xi’an Shiyou University, Xi’an, 710065, China.
Email: congweicw@126.com

Abstract. For the difficulties of cross-link fault diagnosis in complex systems, a fault diagnosis method based on optimised signed directed graph model is proposed. First, the system structure is layered and the control bridge is used to implement a top-down hierarchical structure. The SDG is used to describe the hierarchical structure of the system, and the SDG model is also layered so the fault information is propagated unidirectionally according to the layer. The reverse search strategy based on the fault propagation matrix is used to judge the compatible path, obtain the set of candidate fault sources, use the use availability to objectively evaluate the impact of multiple fault sources to improve the efficiency of troubleshooting. The example analysis shows that the method in this paper can adapt to the fault diagnosis needs of complex systems, and has practical application value for shortening the time of system fault determination and improving the accuracy of troubleshooting.

1. Introduction

A complex system is a whole made up of multiple components. When one component fails, its error information will be transmitted along the physical link, and cause a cascading effect. The initiation factors of system failure are numerous and coupled with each other, and the troubleshooting is focused on accurate diagnosis.

The signed directed graph (SDG)¹ is based on system structure modelling, reflecting the influence relationship between components, and is widely used in system fault diagnosis²⁻⁸. However due to the cross-linking and propagation characteristics of system faults, the practical application of traditional SDG methods in complex system fault diagnosis is limited. First, there are many components in a complex system, and the fault state is prone to combination explosion⁹ which leads to low efficiency of fault search; second, most literature use the methods such as fault probability, compatible channel propagation probability to evaluate the impact of the fault source, but the determination of the fault probability and propagation probability lacks an objective basis which affects the efficiency of troubleshooting.

In order to solve the problems of large search space of complex system fault models and low troubleshooting efficiency of multiple fault sources, this paper proposes an Optimised Signed Directed Graph (OSDG). Firstly a layered method of system structure is proposed and a control bridge is introduced to implement top-down hierarchical fault diagnosis from the system level to the component level, reducing the complexity of system fault modelling and fault reasoning. Secondly, the SDG model is integrated with the hierarchical system structure, and the SDG model is hierarchically optimised, so the fault information is unidirectionally propagated in layers, and the fault search efficiency is improved. The example analysis shows that the method in this paper can adapt to the fault
diagnosis needs of complex systems, and has practical application value for improving the accuracy of troubleshooting.

2. OSDG Modelling Method

2.1. Introduction to SDG Model

**Definition 1**: SDG model definition\(^\[9,10\]\) is as follows:

\[
G = (V, E, \varphi)
\]  

Where \(V = \{v_1, v_2, \ldots, v_n\}\) is the node-set, \(E = \{e_{i,j}\}\) is the directed edge set, \(\varphi: \varphi(e_{i,j}) (e_{i,j} \in E)\), \(\varphi \rightarrow \{+, -\}\) is the sign of the branch \(e_{i,j}\), “+” indicates the positive influence of node \(v_i\) to node \(v_j\) and “−” indicates the negative influence of node \(v_i\) to node \(v_j\).

**Definition 2**: The sign of the node \(v_k\) is represented by the function \(\phi\):

\[
\phi(v_k) = \begin{cases} 
1, & Y - \bar{Y} \geq \epsilon \\
0, & |Y - \bar{Y}| < \epsilon \\
-1, & \bar{Y} - Y \geq \epsilon
\end{cases}
\]  

Where \(Y\) is the test value of node \(v_k\), \(\bar{Y}\) is the theoretical value of node \(v_k\), \(\epsilon\) is the threshold of node \(v_k\) in a normal state. The value 1 and -1 indicates node \(v_k\) fault and the value 0 means \(v_k\) normal.

**Definition 3**: The antecedent set of \(A_i\) is composed of all nodes reaching \(v_i\) and the reachable set of \(R_i\) is composed of all nodes reachable from \(v_i\).

**Definition 4**: Fault propagation matrix\(^{[10]}\) describes the propagation relationship of node faults. Suppose the SDG graph has \(n\) nodes and the fault propagation matrix is an \(n\) order matrix \(P = (p_{ij})_{n \times n}\) and the value of \(p_{ij}\) is defined:

\[
p_{ij} = \begin{cases} 
\varphi(e_{v_i-v_j}) & v_i R v_j \\
0 & v_i \bar{R} v_j
\end{cases}
\]  

Where \(R\) and \(\bar{R}\) are respectively reachable and unreachable signs. If \(v_i\) reaches \(v_j\), \(p_{ij}\) is \(\varphi(e_{v_i-v_j})\), that is the of all branch symbols from \(v_i\) to \(v_j\), otherwise it is recorded as 0. Therefore the value of \(p_{ij}\) may have 1, -1 and 0 respectively, indicating that \(v_i\) enhances, weakens and has no effect on \(v_j\).

**Definition 5**: In the SDG model if \(\phi(v_k) \neq 0\) then the node \(v_k\) is regarded as a fault, if \(\phi(v_l)\varphi(e_{i,j})\phi(v_j) = +\) then \(e_{i,j}\) is a compatible branch, multiple compatible branches constitute a compatible path and faults must be propagated through the compatible path.

2.2. SDG Modelling Method

This paper proposes a system structure layering method to reduce the difficulty of SDG modelling. Figure 1 describes a 3-level hierarchical structure. The system includes multiple subsystems, each subsystem consists of several components, and the components include several parts. Each subsystem has at least one control bridge to interact with other subsystems. The system-level fault diagnosis object is the control bridge in each subsystem. When the control bridge fails the fault diagnosis of the subsystem where the control bridge is located is performed.

![Figure 1. Diagram of the system structure in three levels](image)
The SDG modelling method is applicable to the system level, subsystem level and component level of the system structure. The specific steps are as follow:

Describe the system modules as a directed graph \( G = (V, E) \), where \( V = \{v_i\} \) is a set of nodes, \( E = \{e_{ij}\} \) is the connection relationship between modules.

According to the state change relationship of the module the function \( \varphi \rightarrow \{+,-\} \) is used to determine the sign of the branch \( e_{ij} \), and the positive effect or negative effect of node \( v_i \) on node \( v_j \) is represented by “+” or “-” in the directed graph \( G \).

### 2.3. SDG Model Optimisation

The specific method of SDG model layering is as follows:

**Step 1**: Use \( n \)-order adjacency matrix \( A = (a_{ij})_{n \times n} \) to represent SDG, element \( a_{ij} = 1 \) means node \( v_i \) can directly reach \( v_j \), otherwise it is unreachable. The method of transforming the adjacency matrix \( A \) into the fault propagation matrix \( P^{[11]} \) is as follows:

\[
P = E + A + A^2 + \cdots + A^{n-1}
\]

Where \( E \) is the \( n \)-th order unit matrix.

**Step 2**: Calculate the reachable set \( R \), prior set \( A \) and common set \( C \) of each node in matrix \( P \). If \( C(v_j) = A(v_j) \) then the node \( v_i \) is the layer one node, that is \( L_1 = \{v_i | C(v_j) = A(v_j)\} \).

**Step 3**: In the matrix \( P \) the layered node \( v_i \) and the directed edge connected to \( v_i \) are removed to get a new SDG.

**Step 4**: Repeat step 1 to 3 until all nodes are layered to obtain a layered optimised SDG model.

### 3. Fault Diagnosis based on OSDG

The steps of fault diagnosis based on the OSDG model are as follows:

**Step 1**: Construct the OSDG model. Construct the layered system structure, calculate the fault propagation matrix \( P^{[11]} \) and perform layered optimisation to obtain the OSDG model.

**Step 2**: Determine the set of alarm nodes. When the system generates a fault alarm, the alarm nodes are stored in the set \( S = \{v_i\} \).

**Step 3**: Construct a sample vector. Let the node measured state vector \( T = [t_1, t_2, \ldots, t_n] \), \( t_j \) be the \( j \)-th node, and the calculation method of the node sign is as Formula (2).

**Step 4**: Search for the maximum compatible root tree of node \( v_j \). Let \( v_x \) be the \( j \)-th node, the compatible information of \( v_x \) and \( i \)-th node \( v_i \) is denoted as \( B_{ij}(i) \), the value of each element in \( B_{ij}(i) \) is 0, ± 1. The node-set in the \( v_x \) compatible root tree is \( P(v_x) = \{v_i | B_{ij}(i) \neq 0\} \).

**Step 5**: Handle other alarm nodes. Take other unprocessed alarm nodes from the alarm node-set \( T_A \) and repeat step 4 and 5 until all alarm nodes have been processed. The intersection of all compatible root tree nodes is recorded as \( K \), and the others are stored in the set \( Q \).

**Step 6**: Evaluate the impact of alternative fault sources. Here, use availability\(^{[12]}\) is used to evaluate the impact of multiple alternative fault sources on the fault, which is defined as:

\[
a = T_w/(T_w + T_m)
\]

Where \( T_w \) is the sum of component working time, \( T_m \) is the total of component failure time. \( T_w \) and \( T_m \) are recorded in maintenance practice.

### 4. Fault Analysis of Integrated Avionics System

#### 4.1. Structure of Integrated Avionics System

The integrated avionics system’s structure layering method is shown in Figure 2. Due to space limitations only two subsystems are used as examples.

The system layer includes bridge components such as navigation computers, electronic warfare (EW) processor. The fault diagnosis of this layer should be located to the bridge components. The subsystem layer is composed of the internal components of each subsystem. For example the CNI
subsystem consists of beacon receivers and airborne navigation equipment, etc. The fault diagnosis of this layer is to find component faults in this subsystem.

![Diagram of integrated avionics system](image)

**Figure 2.** Diagram of integrated avionics system

The method in this paper applies to the fault diagnosis of the system layer and the subsystem layer. The following takes the system layer fault diagnosis as an example. To facilitate discussion, the components of the system are shown in Table 1.

| number | name                  | number | name                          |
|--------|-----------------------|--------|-------------------------------|
| 1      | atmospheric computer  | 8      | navigation management computer|
| 2      | inertial navigation computer | 9  | store management computer    |
| 3      | target processor      | 10     | data transmission computer    |
| 4      | navigation computers  | 11     | operation input processor     |
| 5      | EW processor          | 12     | warning output computer       |
| 6      | status monitoring computer | 13 | display control processor    |
| 7      | fire control computer |        |                               |

The fire control computer is the most complex component in the integrated avionics system. During a power-on inspection on the ground, the maintenance staff found that the attack area of the medium-range air-to-air missile was too large. This is a typical system failure caused by fault propagation. Use the method proposed in this paper to find the source of the fault that caused the problem.

### 4.2. Fault Analysis

#### 4.2.1. Construct the OSDG model of the integrated avionics system

Step 1: Abstract the components of system into a graph of node-sets \( V = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}, v_{12}, v_{13}\} \), the element index in the node-set \( V \) is the same as the part number in Table 1. According to the function and information interaction relationship of the integrated avionics system, the directed graph \( G \) is obtained; then the function \( \varphi \rightarrow \{+, -\} \) is used to determine the symbol of the branch \( e_{i,j} \) to obtain the symbolic directed graph as shown in Figure 3.
Figure 3. SDG diagram of integrated avionics system

*Step 2:* Use Formula (3) to calculate the fault propagation matrix $P$:

$$P = \begin{bmatrix}
+1 & 0 & 0 & 0 & 0 & +1 & +1 & 0 & 0 & 0 & 0 & +1 \\
0 & +1 & 0 & 0 & 0 & +1 & +1 & 0 & 0 & 0 & 0 & +1 \\
0 & 0 & +1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & +1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & +1 \\
0 & 0 & 0 & 0 & +1 & 0 & 0 & 0 & 0 & 0 & 0 & +1 \\
0 & 0 & 0 & 0 & 0 & +1 & 0 & 0 & 0 & 0 & +1 & +1 \\
-1 & -1 & -1 & +1 & +1 & -1 & -1 & +1 & -1 & +1 & -1 & -1 \\
0 & +1 & 0 & 0 & 0 & +1 & 0 & -1 & 0 & +1 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & +1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & +1 
\end{bmatrix}$$

*Step 3:* Calculate the reachable set $R$, prior set $A$ and common set $C$ of the fault dependency matrix $P$ as shown in Table 2.

| $v_i$  | $R_1(v_i)$ | $A_1(v_i)$ | $C_1(v_i)$ |
|-------|-----------|-----------|-----------|
| $v_1$ | 1,7,8,13  | 1,10      | 1         |
| $v_2$ | 2,7,8,13  | 2,10      | 2         |
| $v_3$ | 3,7,13    | 3,10,11   | 3         |
| $v_4$ | 4,8,13    | 4,10      | 4         |
| $v_5$ | 5,12      | 5,10      | 5         |
| $v_6$ | 6,12      | 6,10      | 6         |
| $v_7$ | 7,13      | 1,2,3,7,9,10,11 | 7 |
| $v_8$ | 8,13      | 1,2,4,8,10 | 8 |
| $v_9$ | 7,9,13    | 9,10,11   | 9         |
| $v_{10}$ | 1,2,3,4,5,6,7,8,9,10,11,12,13 | 10      | 10        |
| $v_{11}$ | 3,7,9,11,13 | 10,11    | 11        |
| $v_{12}$ | 12        | 10,12     | 12        |
| $v_{13}$ | 13        | 1,2,3,4,7,8,9,10,11,13 | 13 |

Since $C_1(v_{10}) = A_1(v_{10}) = 10$ the node $v_{10}$ is the first layer node $L_1 = \{v_{10}\}$ and so on, the layered optimised OSDG model is obtained as shown in Figure 4.
4.2.2. Fault reasoning. First, from the fault description, the system alarm node-set $T_A = \{v_t\}$, the corresponding node symbol according to the fault phenomenon, thereby defining the fault sample $T = [0 + 1 - 1 0 0 0 + 1 0 + 1 + 1 0 0 - 1]$.

Secondly, it is known from Figure 4 that the alarm node is at the $L_4$ layer and the inference from the $L_4$ layer to the $L_1$ layer is reversed. According to the definition of the compatible path, $\phi(v_0)\phi(e_9 \rightarrow e_7)\phi(v_7) = +$ and $\phi(v_{10})\phi(e_{10} \rightarrow e_2)\phi(v_2)\phi(v_2)\phi(e_2 \rightarrow e_7)\phi(v_7) = +$ are compatible. The union of compatible path nodes $K = \{v_2, v_9, v_{10}\}$, intersection $Q = \emptyset$.

Finally, calculate the availability of $v_2$, $v_9$ and $v_{10}$ according to Formula(5): $a_{v_2} = \frac{621}{621+106} = 0.8542$, $a_{v_9} = \frac{479}{479+70} = 0.8704$, $a_{v_{10}} = \frac{550}{550+103} = 0.8423$.

4.2.3. The alternative fault source set is $K = \{v_{10}, v_2, v_9\}$. When troubleshooting $v_{10}$ is first checked, the function of this node is to bind the missile envelope data and initialization parameters to the fire control computer. After inspection it is found that the software version number of this node does not match the software version in the fire control computer. The fault disappears after re-load the new version of the missile envelope data and power-on again.

5. Conclusions

First, Propose a hierarchical method of system structure, introduce a control bridge to implement top-down fault diagnosis from system level to component level. Suppose the system has 10 subsystems, each of which has 20 components. The inference complexity $O(10^{2} + 20^{2})$ is much smaller than the inference complexity $O(10^{2} \times 20^{2})$ before the system structure is layered.

Secondly, The SDG model layering method is proposed. Based on the system structure layering, the SDG model describing hierarchical system structure is layered again so the fault information is propagated unidirectionally. Suppose that the SDG graph of the subsystem has 7 layers and the fault alarm node is on the 5th layer. There are 14 nodes from this layer to its highest level, then the inference complexity is $O(14^{2})$ less than $O(20^{2})$ before the SDG is layered.

Finally, A backward search strategy based on a fault propagation matrix is used to determine compatible paths, obtain a set of candidate fault sources, introduce the “use availability” to objectively evaluate the impact of multiple fault sources, and improve troubleshooting efficiency.

Application examples show that the OSDG model can adapt to the fault diagnosis needs of complex systems, and has practical application value for improving the troubleshooting accuracy.

6. References

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