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Description of System Fault Behavior Model Based on Polychromatic Sets

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Abstract: The system fault behavior model was investigated by the author first. System fault behavior model describes the occurrence and development process of malfunction in product, and analyzes the transmission process of unit malfunction in system and effects of various factors on system. In order to realize simulation of system fault behavior, it is necessary to perform formalized process of system fault behavior model, so as to acquire the mathematic description required by computer simulation. So the formalized description of fault behavior model (FBM) based on polychromatic sets theory was introduced. With consideration of the characteristics of model hierarchy and information variety of current fault behavior model, the method of polychromatic sets and polychromatic graph was adopted to describe the information such as objects, behaviors, restriction and relevant correlation in model. Formalized description of fault behavior model and convenient model for computer expression and operation were realized, which laid down a further solid foundation for simulation of system fault behavior.

Keywords: Fault Behavior, polychromatic sets, reliability, model, formalize.

1 Introduction

System reliability research is gradually making the transit of focusing on ”fault time” to focusing on ”fault process”. The researches on reliability models of micro failure mechanism [1,3] and macro fault behavior [4,7] have become hot topics. The system fault behavior [8] model describes the occurrence and development process of system fault in term of the behavior, and also presents the effect of basic unit failure on the whole system. It is a new orientation for system reliability research. There are currently two branches in research of this orientation, one branch is fault behavior modeling based on time competition mechanism [9,10], of which the basic idea is to determine the failure mechanism causing first system fault through time competition on the basis of bottom layer failure physical model, therefore establish the relationship between failure mechanism of components/parts and system fault behavior. The other branch is fault behavior modeling based on fault propagation [11,14], which is focused on the propagate process between circuit level/equipment level and the entire system level.

The system fault behavior model [12] established on the basis of the second branch mentioned above is an entity containing structure, behavior and environmental information, and is a complicated entity that features special function and is formed as per successive layers structure based on properties (behavior and environment, i.e. restriction conditions) of all constituent elements (objects). The model contains numerous aspects of information, such as object, behavior and restriction, etc. It features hierarchy and information variety. If traditional set theory is adopted to replace its formalized description, it is only possible to describe object, behavior and restriction in model individually, rather than reflect correlation between them, especially it is impossible to display correlation between behavior condition and object of different layers, this makes it difficult to perform accurate mathematic description in computer simulation. The polychromatic sets proposed [15,16] by Russian professor Pavlov V. V. is based on the traditional set theory, and clearly describes the property of set itself and its constituent elements and their correlation by adding color of entire set and elements in set. It features two characteristics: 1. Adopts mathematical model of the

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same formation for description, and feature high degree of generality; 2. It is a hierarchical system, which organizes and processes information in set layer and logic layer, and solves the specific quantity and size issue of bottom layer at quantity layer, so as to process huge amount of information and simulate large-size complicated product. The characteristics of polychromatic sets are applicable for the feature of FBM, such as hierarchy and information variety. At present, this idea is used in aspects such as modeling and analysis of processing system, product assembling sequence simulation, product manufacturing process, conceptual design of machinery product, and version management of collaborative design, etc [17,20].

Therefore, adopting polychromatic sets theory, this paper has described various characteristics of different layers in system fault behavior model, and correlation and connection between characteristics of layers, and has researched the formalized description method of system fault behavior model based on polychromatic sets. The rest of this paper is organized as follows: Section 2 investigates system fault behavior model, Section 3 introduces the overview of polychromatic sets theory, Section 4 discusses the description of FBM model based on polychromatic sets theory in detail. At last, it is a case study.

2 System Fault Behavior Model

The system fault behavior refers to the status changes that a system deviates from its preset functions and are the activities and status changes of the components, interaction on each other and the dynamic process that the fault spread continuously when the system fault happens. It shows the changes of the system status over time, and is not only the reflection of effects of both external and internal factors on the fault behavior of the units of the system but also the reflection of the interrelationship among the fault behaviors of the basic units, i.e., the occurrence of a fault behavior caused by another fault behavior. The fault behavior model describes the evolution and changes of the system behavior when any internal unit of a system breaks down or the external interference exists, i.e., describes the course of occurrence, development and spread of a fault in the system, so as to analyze and obtain the effects of various faults on the system. The system fault behavior model (FBM) is defined as two-tuples [12]

FBM = (OBJS, B)

thereof, OBJS is the set of system objects, including various levels of units comprising the product; B is the fault behavior set, different fault behaviors belongs to different objects, so the fault behaviors are co-affected by both external and internal factors. The object set reflects the intrinsic attributes of the system, while the fault behavior set reflects the behavioral change of the system, embodying the conditions of external stimulus sustained when the system is running, and the transfer of the system status over time.

The framework of FMB is shown in Fig. 2.1.

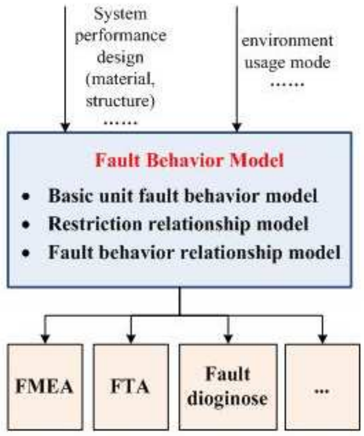

Fig. 2.1: The framework of FBM

FBM includes three parts:

- Basic unit fault behaviour model
- Restriction relationship model
- Fault behaviour relationship model

Basic unit fault behavior model is for every unit composed of the system. Restriction relationship model applies to the factors in external influence factors sets. Fault behavior relationship model is for all kinds of trigger relationships between fault behaviors. Restriction relationship model produces restriction condition on basic unit fault behavior model, all basic unit fault behavior models joint into Basic unit fault behavior model is for every unit composed of the system. Restriction relationship model applies to the factors in external influence factors sets. Fault behavior relationship model is for all kinds of trigger relationships between fault behaviors. Restriction relationship model produces restriction condition on basic unit fault behavior model, all basic unit fault behavior models joint into a whole then through fault behavior relationship model. Thus the system whole fault behavior model could be built. On the basis of comprehensive consideration of internal/external factors affecting system malfunction, the system fault behavior model is established as a three-layer structure containing system structure layer, behavior layer and restriction layer, as shown in Fig. 2.2.

The entire model describes system fault behavior process and fault information propagation, the structural layer reflects the static structure between all constituent units of system; behavior layer reflects the dynamic fault behavior process of system and its constituent units; the

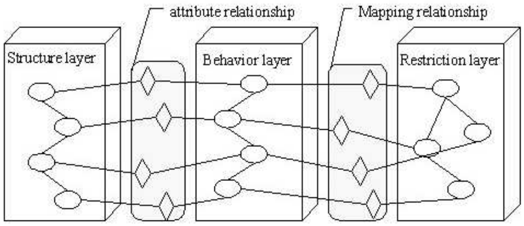

Fig. 2.2: Three-layer structure of system fault behavior model

restriction layer reflects the restriction upon system and its constituent units during operation. The entire model adequately expresses the hierarchic relationship and correlation of system, and reflects the dynamic behavior process featuring triggering.

3 Polychromatic Sets Theory

Polychromatic sets is a information processing tool, of which the core idea is to simulate different objects by using standard mathematical model, the method is to improve traditional set theory by tools such as symbolic logic, matrix theory and fuzzy mathematics, so that it can describe properties of set itself and its constituent elements and correlation between properties of set itself and its constituent elements. Polychromatic sets is actually a mathematical model describing constitutionality relationship and coherence in system hierarchy, it respectively abstracts system and its constituent elements, the constitutionality relationship and coherence in system hierarchy as polychromatic sets and its constituent elements, relationship between entire set property and constituent elements property and relationship between its constituent elements property. It actually is an abstraction of hierarchy relationship of objects in realistic world. Relevant concepts of polychromatic sets theory is described as follows [21,23].

3.1 Polychromatic Sets

Traditional set represents all elements, which are expressed as:

$$A = (a_1, \ldots, a_i, \ldots, a_n) \quad (1)$$

In Equation 1, only names of elements are different, it is impossible to represent different properties of elements. Polychromatic Sets expresses properties of research objects and constituent elements by assigning different colors to set itself and its constituent elements. Color set corresponding to overall set A and its constituent elements $a_i \in A$ are respectively marked as $F(A)$ (referred to as unified color of Polychromatic Sets) and $F(a_i)$ (referred to as individual color of element a_i), its composition is:

$$F(A) = (F_1(A), F_2(A), \ldots, F_p(A)) \quad (2)$$

$$F(a_i) = (F_1(a_i), F_2(a_i), \ldots, F_m(a_i)) \quad (3)$$

$F(A)$ and $F(a_i)$ are referred to as colored, and are contained in a unified color set,

$$F \supseteq F(A); F(a_i) \quad i = 1, 2, \ldots, n \quad (4)$$

$F(A)$ and $F(a_i)$ are respectively referred to as unified color of Polychromatic Sets and individual color of element a_i. When expressing simulation object, they respectively correspond to j^{th} property of object A and element a_i.

Correlation between composition of unified color of Polychromatic Sets and composition of individual color of elements, relationship between unified color and its constituent elements and the composition of all entities in which unified color exists can be respectively expressed as: $[F(a) \times F(A)]$, $[A \times F(A)]$ and $[A \times A(F)]$. In which, $A(F)$ is the set of all entities of unified color. See details as per literature [19,21]. In summary of the above mentioned, Polychromatic Sets can be expressed as:

$$PS = (A, F(a), F(A), [A \times F(a)], [A \times F(A)], [A \times A(F)]) \quad (5)$$

3.2 Polychromatic Graph

Common graph can be expressed as $G = (A, C)$, in which A is the set of nodes, C is the set of connected node edges, but this kind of traditional graph theory tool cannot describe composition of node and edge in plot while describe different properties of node and edge in plot. In polychromatic graph, any node and edge can be painted with different colors simultaneously, this is the difference between polychromatic graph and achromatic graph. As color features property of corresponding objects, different colors can describe different properties, therefore, the i^{th}

color corresponds to property F_i and the j^{th} color corresponds to property F_j, etc.

Under normal conditions, polychromatic graph (PG) consists of $(F(G), PS_A, PS_C)$. In which, $F(G)$ describes overall property of polychromatic graph, while PS_A describes node and its property, and PS_C describes edge and its property. In which, PS_A and PS_C can be respectively expressed as:

$$PS_A = (A, F(a), F(A), [A \times F(a)], [A \times F(A)], [A \times A(F)]) \quad (6)$$

$$PS_C = (C, F(c), F(C), [C \times F(c)], [C \times F(C)], [C \times C(F)]) \quad (7)$$

In which, F_A is color of node and F_C is color of edge

In case edge of polychromatic graph PG is colorless, then $F(G) = F(A)$; in case node is colorless, then $F(G) = F(C)$; in case both node and edge are colorless, then $F(G) = \hat{O}$, at the moment, polychromatic graph PG can be expressed by common graph $G = (A, C)$.

4 FBM Model Description Based on Polychromatic Sets Theory

As analyzed from the point of view of system, FBM model is a complicated entity formed on the basis all its constituent elements and attributes as per successive layers structure, expression of its layering is shown in Fig. 4.1.

Its formalized description must describe correlation in hierarchy accurately and completely, advantage of Polychromatic Sets theory just meets these requirements.

4.1 Formalized description of FBM model

Regarding the hierarchic relationship of FBM model, polychromatic graph node is used to represent object in model, that is product component, i.e. structural layer; different colors applied on node represents different attributes of object, including behavior and restriction of object, i.e. behavior layer and restriction layer; edge adopting polychromatic graph represents connection relationship between objects in model, different colors applied on edge represent connection type, including inference relationship and triggering relationship. Therefore, in accordance with demand, structural description of FBM model can be expressed as:

$$PG = (A, F(a), F(A), F(a) \times F(A), A \times F(A), F(A) \times F(A), C, F(c), C \times F(c)) \quad (8)$$

In which, $A = (a_0, a_1, \ldots, a_n)$ represents object set in model;

$F(a) = (F_1(a), F_2(a), \ldots, F_m(a))$ represents individual behavior set of object in model;

$F(A) = (F_1(A), F_2(A), \ldots, F_p(A))$ represents overall behavior set of object in model;

$C = (c_{i(j)} | \, 0 \le i \le n, \, 0 \le j \le n)$ represents connection relationship between objects, $c_{i(j)}$ represents connection relationship between objects a_i and a_j ;

$F(c) = (F_1(c), F_2(c), \ldots, F_k(c))$ represents connection relationship between objects in model, here $k = 2$;

Products can be disassembled in different layers to get its components. Therefore, it can be deemed that there are certain known components, which are basic structural elements of product, and feature definite description. In product design, component can be gear, shaft and bearing, etc, or parts consisting components. Selection of component is related to knowledge and state of the art of design field and designer, here component (object) is expressed by a_i, their set is expressed by A. Set of various attributes of component (object) a_i can correspond to concept of individual coloring in polychromatic Sets, and is expressed as $F(a_i)$, which includes behavior and relevant restriction conditions of component (object) a_i. Therefore, component (object) set S_a can be expressed as:

$$S_a = \{< a_i, F(a_i) > | i = 1, 2, \ldots, n\} \quad (9)$$

Regarding the FBM model structure shown in Fig. 4.1, restriction node and behavior node of middle and top layers of three adjacent layers from top to bottom are merged with corresponding object node of bottom layer into one node, and is expressed in form of ordered pair. Node i_k of layer k regarding node j_{k-1} of layer $k-1$ as father node after merging is expressed as $< dp(k, i_k, j_{k-1}), F(dp(k, i_k, j_{k-1})) >$ by using ordered pair. In which, $dp(k, i_k, j_{k-1})$ represents bottom layer object node, $F(dp(k, i_k, j_{k-1}))$ represents top layer restriction node and behavior node corresponding to object node. Thus, FBM model structure can be expressed as the formation in Fig. 4.2.

As shown in Fig. 4.2, mathematic description of FBM model recursive form is as follows:

$$< dp(0,0,0), F(dp(0,0,0)) >$$
$$= \bigwedge_{i_1=1}^{n_1} \langle dp(1, i_1, 0), F(dp(1, i_1, 0)) \rangle$$
$$\forall k (1 \le k \le n), \forall i_k (1 \le i_k \le n_k)$$
$$< dp(k, i_k, j_{k-1}), F(dp(k, i_k, j_{k-1})) >$$
$$= \bigwedge_{i_{k=1}=1}^{n(k+1, i_k)} \langle dp(k+1, i_{k+1}, i_k), F(dp(k+1, i_{k+1}, i_k)) \rangle$$

$$n_0 = 1, \quad n_k = \sum_{i_{k-1}=1}^{n_{k-1}} n(k, i_{k-1}) \quad (10)$$

In which, $n(k+1, i_k)$ represents number of son nodes of node i_k of layer k ; n_k represents number of all nodes of layer k.

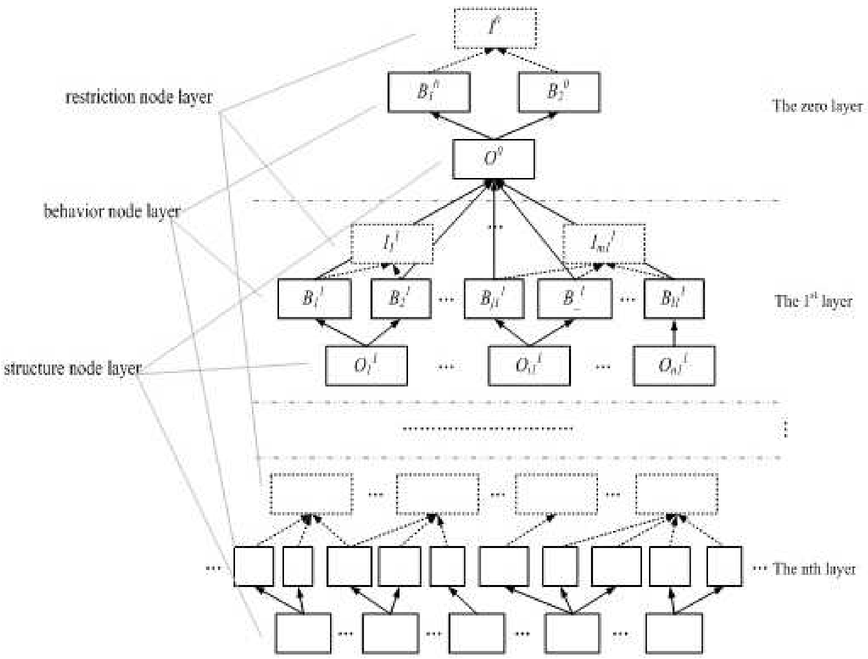

Fig. 4.1: Three-layer structure of system fault behavior model

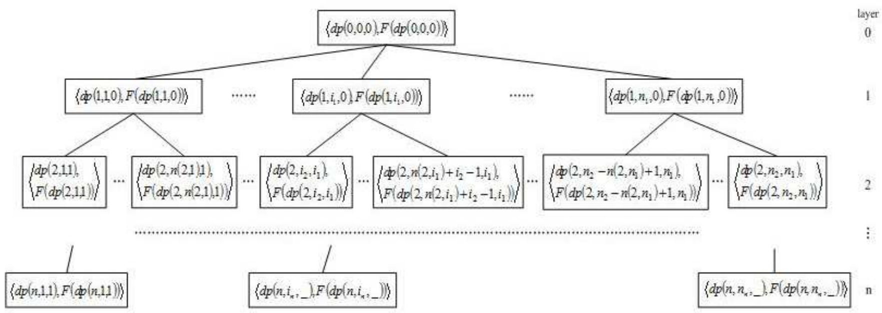

Fig. 4.2: The formalized description of FBM structure

If $\forall l\,(1 \le l \le n)$ and $\forall i_l\,(1 \le i_l \le n_l)$ meet following conditions:

$$\langle dp(l,i_l,j_{l-1}), F(dp(l,i_l,j_{l-1}))\rangle \in S_a \qquad (11)$$

Then the node is leaf node (terminal node), which is the terminal condition for disassembling of branches of different depths in model.

4.2 Correlation Between Different Elements in FBM Model

Correlation between different elements in FBM model includes several types as follows. In which, $A = dp(k,i_k,j_{k-1})$.

$F(a) \times F(A)$ represents the relationship between $F(dp(k,i_k,j_{k-1}))$ and $F(dp(k+1,i_{k+1},i_k))$, i.e. correlation between element attributes of adjacent layers (behavior of objects of adjacent layer), as shown in Equation 12.

$$(c_{ij})_{n(k+1,ik)\times p} = [F(dp(k+1,i_{k+1},i_k)) \times F(dp(k,i_k,j_{k-1}))] \qquad (12)$$

$$= \begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1p} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{ip} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{n(k+1,j_k)1} & \cdots & c_{n(k+1,j_k)j} & \cdots & c_{n(k+1,j_k)p} \end{bmatrix}^{F_1(A)\ \dots\ F_j(A)\ \dots\ F_p(A)} \begin{matrix} F(dp(k+1,1,i_k)) \\ \vdots \\ F(dp(k+1,i,i_k)) \\ \vdots \\ F(dp(k+1,n(k+1,i_k),i_k)) \end{matrix}$$

$A \times F(A)$ represents the relationship between $F(dp(k,i_k,j_{k-1}))$ and $\mathrm{dp}(k+1,i_{k+1},i_k)$, i.e. correlation between top layer elements attributes and bottom layer constituent elements (behavior of top layer object and bottom layer object), as shown in Equation 13.

$$(c_{ij})_{n(k+1,ik)\times p} = [dp(k+1,i_{k+1},i_k) \times F(dp(k,i_k,j_{k-1}))] \quad (13)$$

$$= \begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1p} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{ip} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{n(k+1,j_k)1} & \cdots & c_{n(k+1,j_k)j} & \cdots & c_{n(k+1,j_k)p} \end{bmatrix}^{F_1(A)\ \dots\ F_j(A)\ \dots\ F_p(A)} \begin{matrix} dp(k+1,1,i_k) \\ \vdots \\ dp(k+1,i,i_k) \\ \vdots \\ dp(k+1,n(k+1,i_k),i_k) \end{matrix}$$

$F(A) \times F(A)$ represents the relationship between $F(dp(k,i_k,j_{k-1}))$ and $F(dp(k,i_k,j_{k-1}))$, i.e. correlation between different object behavior of the same layer.

$C \times F(C)$ represents the relationship between edge and restriction types represented by edge, as shown in Equation **??**, in which l represents number of elements in C.

$$(c_{ij})_{C,F(c)} = \begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1k} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{ik} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{l1} & \cdots & c_{lj} & \cdots & c_{lk} \end{bmatrix}^{F_1(c)\ \dots\ F_j(c)\ \dots\ F_k(c)} \begin{matrix} c_1 \\ \vdots \\ c_i \\ \vdots \\ c_l \end{matrix} \quad (14)$$

All components in the above model can be expressed by adopting matrix, through filling-out of all information matrixes, all models are transformed into matrix expression, and more important, it is only necessary to expand relevant matrix rather than modify model for complicated structure.

5 Example Analysis

Taking GK0058-1 model high-speed lock type sewing machine [24] as an example, perform simple analysis of its take-up mechanism and thread hooking mechanism, so as to embody possible malfunction behavior that may occur during operation. Computer simulation diagram of take-up mechanism and thread hooking mechanism of sewing machine is shown in Fig. 5.1.

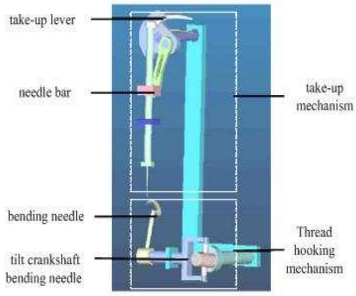

Fig. 5.1: The diagram of take-up mechanism and thread hooking mechanism of sewing machine

Lock type sewing machine consists of multiple mechanisms such as take-up mechanism, thread hooking mechanism and feeding mechanism, which jointly complete sewing function. In which take-up mechanism and thread hooking mechanism are the core parts forming lock-stitch. The take-up mechanism controls surface thread, thread hooking mechanism controls bottom thread so that bottom thread and surface thread interlace mutually to form lock-stitch. The take-up mechanism consists of take-up lever and needle bar, during operation, in case operation environment of needle bar is not adequately lubricated, tilt thread hole trace will be caused. Similarly, in case of inadequate lubrication, bottom thread movement trace of tilt crankshaft bending needle will have error, therefore causing occurrence of behavior of dropped stitch. In case number of dropped stitches reaches certain level, it is impossible to form lock-stitch required. Its fault behavior model hierarchy is shown in Fig. 5.2

Nodes in Fig. 5.2 are expressed as follows by using the form in Fig. 4.2:

$dp(0,0,0)$ is chain type sewing machine; $F(dp(0,0,0))$ is to form chain-stitch or chain-stitch failing to meet requirements; $dp(1,1,0)$ is take-up mechanism; $F(dp(1,1,0))$ is tighten/release surface thread or thread cast-off; $dp(1,2,0)$ is thread hooking mechanism; $F(dp(1,2,0))$ is interlace or cast-off of surface thread or bottom thread; $dp(1,3,0))$ is feeding mechanism; $F(dp(1,3,0))$ is relative movement of stitch thread and sewing material; ...; $dp(2,1,1)$ is take-up lever; $F(dp(2,1,1))$ is control of surface thread; $dp(2,2,1)$ is needle bar mechanism; $F(dp(2,2,1))$ is form mormal thread bole trace or wrong thread hole trace; $dp(2,3,2)$ is tilt crankshaft bending needle mechanism; $F(dp(2,3,2))$ is to form normal bottom thread movement trace or wrong bottom thread movement trace; $dp(2,4,2)$ is bending needle; $F(dp(2,4,2))$ is control of

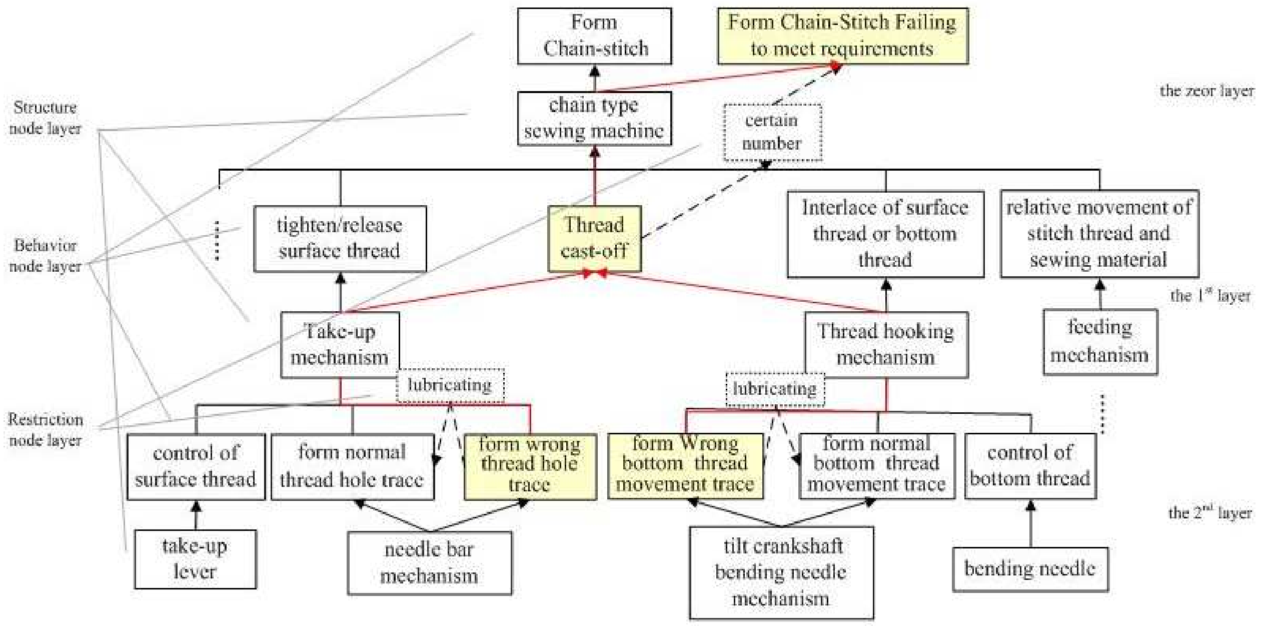

Fig. 5.2: FBM of Sewing machine (part)

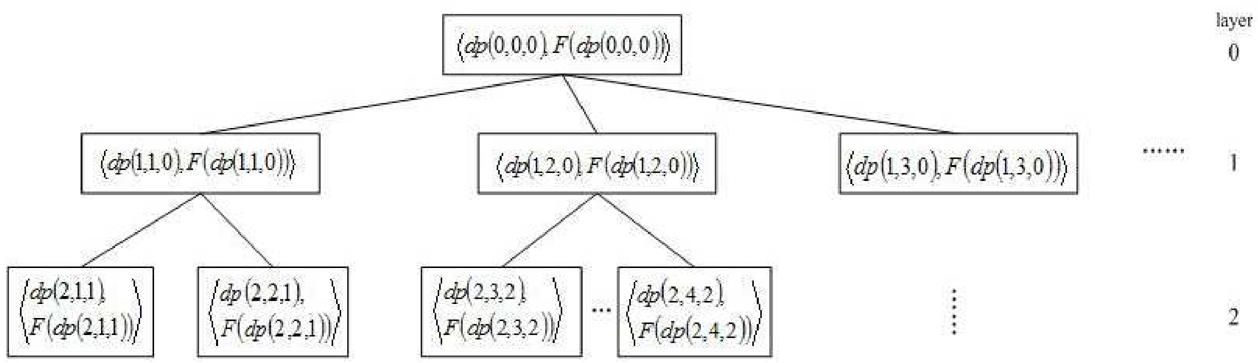

Fig. 5.3: FBM of Sewing machine (part)

bottom thread; On the basis of above mentioned symbols, it is easy to give mathematic description shown in Fig. 5.3.

In accordance with definition of polychromatic Sets, Boolean Vector expression of each carrier can be acquired, for example, for the first layer:

$$F(a) = \{F(dp(1,i,(0))) \mid i = 1,2,3\}$$
$$A = \{dp(1,i,(0)) \mid i = 1,2,3\}$$
$$A \times F(a) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$dp(1,1,0) = [1,0,0]$$
$$dp(1,2,0) = [0,1,0]$$
$$dp(1,3,0) = [0,0,1]$$

Thus, system fault behavior model of product can be expressed and analyzed conveniently, accurately and completely in computer.

6 Conclusion

System fault behavior is to describe occurrence and representation of malfunction in terms of behavior, so as to better reflect the dynamic process of system fault behavior occurrence and development. System fault behavior model describes product from three different layers including structural layer, behavior layer and restriction layer, so as to reflect the meaning of system fault behavior. Through establishment of correspondence of unified color/individual color in polychromatic Sets to object information, behavior information and restriction information of different layers in model, this article uses polychromatic Sets for formalized description of system fault behavior model, and establishes mathematic description convenient for computer expression and operation, so that a further solid foundation for simulation of system fault behavior model has been laid down.

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