Visual Monitoring Path Forecasting for Digital Human-Computer Interface in Nuclear Power Plant and its Application

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Abstract: The operators sometimes can not judge next possible monitoring object which would lead to monitoring delay or transfer error in the monitoring digital human-computer interface (DHCI) parameter information process in nuclear power plant(NPP). For this purpose, the Markov process based forecasting path dynamic plan (FPDP) method which included forecasting path model, forecasting path plan algorithm and the calculation method of transfer path success probability was proposed. Then the monitoring transfer behavior of the operators when SGTR(Stream Generator Tube Rupture) occurred abruption accidents is analyzed based on the method proposed in this paper, taking the DHCI as the source node of monitoring task of t time, the transfer path to next monitoring object was obtained successfully to improve the efficiency of monitoring and to minimize the risk of monitoring error, which will also contribute to the analysis of the driving mechanism of operators' monitoring activities, to train simulated for monitoring behavior, and to optimize the digital man-machine interface.

Keywords: Nuclear Power Plant(NPP); Digital Human-Computer Interface; Monitoring Transfer; Forecasting Path; Markov Process

1 FOREWORD

Today, many NPPs are using or plan to use digital control system (DCS). For example, DCS has been successfully used in Jiangsu Tianwan NPP[1], also, the running NPPs of Hongyanhe and Lingdong, and NPPs under construction, that are Shandong Haiyang and Zhejiang Sanmen, all will employ DCS.

DCS, on the basis of computer calculation, is characterized by digital information display, highly integrated human-computer elements, multilevel data processing and automation operation from the view of human-computer interface. So it is more advanced than traditional control system with traditional simulation technique. There is enormous important information, ie parameter information, warning massage, procedures and operating information should be obtained and analyzed to make a decision through monitoring for DHCI in DCS, so operators' monitoring has been becoming the key step for the whole monitoring execution, also it is completely different with the traditional one[2].

DCS brings great challenge to operators in that monitoring error will cause a consequent series of errors in state assessment, response plan and manipulation. Statistics show that 60%-90% system errors and 50%-70% nuclear power accidents are caused by human errors [3].

With regard to operators' monitoring process, this paper proposes FPDP method to predict the next monitoring object according to the current system state so that operators are able to select and reach the next valid monitoring object more rapidly and exactly, it will provide much helping with reducing human errors, improving monitoring efficiency, and also contributing to analyze the driving mechanism of operators' monitoring activities and to optimize the DHCI.

2 FPDP MODEL IN MONITORING PROCESS

FPDP in monitoring process refers to how to rapidly and exactly obtain the next monitoring object each time after monitoring current state or parameter information for NPP system. Investigation and interviews with operators show that there is logical correlations existed between current monitoring object and the next one, namely, the selection of the next monitoring objects depends on the current

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system state or parameter information. That is, operators' monitoring transfer only relates to the current state or parameter information, so Markov process is available to simulate. As the whole monitoring task process is changeable, namely, the monitoring path vary with operators' monitoring transfer, this paper proposes path selection algorithm and the calculation method of Markov transfer path success probability. Forecasting path with high relevance will be selected out of all possible paths as the next monitoring object, a dynamic plan model (Fig.1) is applied to describe the process.
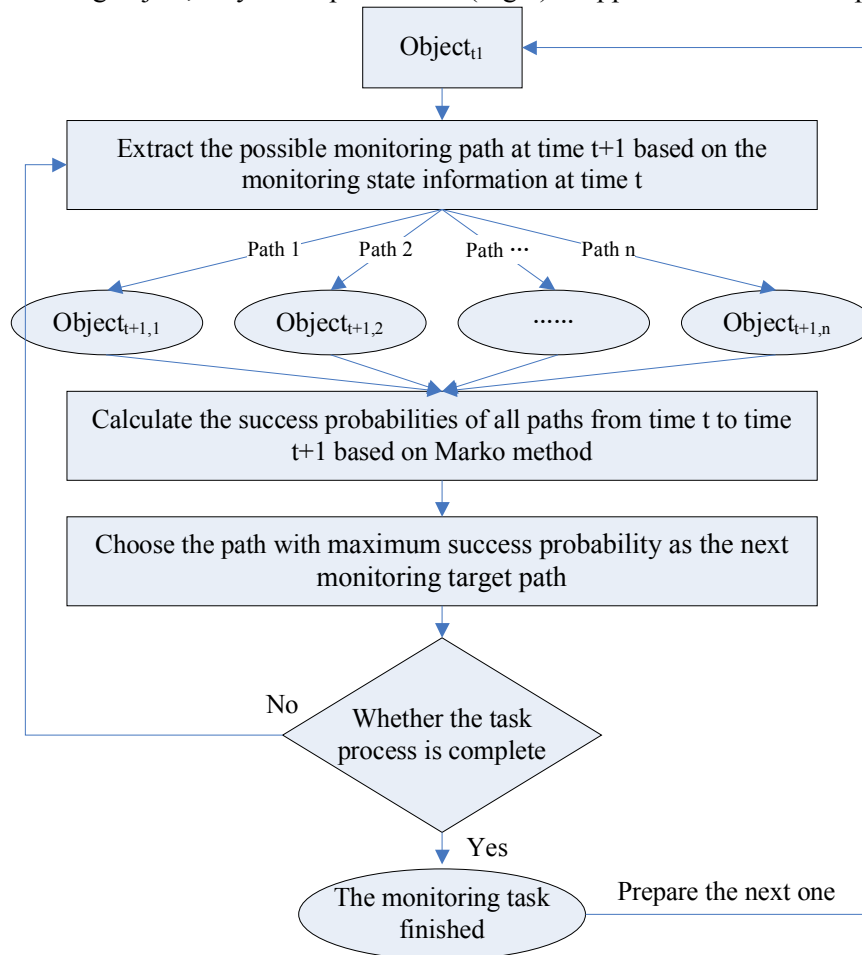
Notations：
$Object_t$: the state information of the monitoring object at time t
$Object_{t+1,n}$: the state information of the would-be monitoring object n at time t+1
Fig.1 Flowchart of FPDP model in monitoring DHCI of NPP

3 FPDP ALGORITHM IN THE MONITORING PROCESS ABOUT DHCI OF NPP

Fig.1 shows that FPDP algorithm searches effective plan through multi paths, obtains next possible monitoring object with maximum success probability and optimal way by dynamic plan method based on current monitoring object. The FPDP algorithm is specified as follows:

At t time, start from the initial object $Object_t$:

(1)Ini_Filter(t,t+1,task_info): screen out information being irrelevant to the task information of current time t and next time t+1, namely, the preliminary selection;

(2)Next_Obj_Pro(t,t+1,n): take monitoring task information at time t as the source point, count the success probability of n possible monitoring paths at time t+1;

(3)Values(t+1,n): file the success probabilities of n possible paths of time t+1 in Values array;

(4)Max(t+1,n): search the maximum success probability out of Values array;

(5)Transfer_route(t+1): Find the path with maximum success probability, and consider it as the next monitoring object;

(6)End(): If the monitoring task is finished, prepare for the next one and transfer to (1);otherwise to (2) and continue monitoring .

4 KEY ALGORITHM OF FPDP IN THE MONITORING PROCESS ABOUT DHCI OF NPP

Algorithm proposed in Chapter 3 shows that there are two key steps in the algorithm: Ini_Filter(t,t+1,task_info) and Next_Obj_Pro(t,t+1,n). We will interpret them in this part.

4.1 Ini_Filter(t,t+1,task_info) Algorithm

As operators have to face tremendous information in the monitoring process, it is essential to sieve out the irrelevant part to simplify search path and to reduce the exaggerated calculation time.

How to sieve out irrelevant part? As we know, tasks (information) with high similarity are relevant, while the others with low similarity are irrelevant. So the key step for operators' screening process is to evaluate tasks' similarity. Generally, operators judge the degree of similarity according to the index pertinence or the semantic similarity or the attribute resemblance of tasks. For example, Gao Ting discussed the grey correlation degree of customers' scarification under business model based on index system[4]; Zheng Yuhua adopted risk index to research the relevance of petroleum engineering projects[5]; Cui Qiwen studied similarity based on semanteme[6]. Inaccuracy would appear when we calculate the tasks' similarity, it would become impossible to extract similarity factors, so the calculation of similarity or association is not dealt in this study to keep the theme. This paper applies multi-branched model to screen.

(1) Build_tree(n): Set up a tree structure with n nodes in database. It is a process that should be analyzed by experts with repeated training and studying. The steps of building tree are: First, mark every tree to differ tasks, cause each tree has its own tree structure. Every node should be marked with its number and task feature, the root node denotes the task source. Second, start from the root node, if found that the current node information and some next task information is correlated, we choose the next correlated task node as the child node of current node. Third, take the child node founded in step forward as parent node and then try to find its child node, the search process would be circled in the same way introduced above until there is no relevant child node anymore. Thus a tree structure is formed, but it still need be repeated trained, studied and revised to form an expert system.

The computer pseudo-code expressions of above process are specified as below:

```
        Initializing: name(tree), identifying(root_node);
        Begin
         While(){
        For (i=first_adject_node;i<=total_adject_node;next_adject_node)
            If between current_node and adject_nodei is relative   Current_node_edge->= adject_nodei;
         }
          For(i=root_node;i<=all_nodes;i++)
    If judge_expert(i,adject_each_node) not relative
            Delect(i,adject_edgei);
          Else if tree_not_edge(i, adject_edgei)
            Add(i,adject_edgei);
        End.
```

(2) Search(tree,relative_edge): Find out all of child nodes to the current task and mark them in terms of tasks' type and features. About the method of marking, two arrays are applied to respectively restore the information of current node and its child node sequences. The computer pseudo-code expressions of this process are specified as follows:

```
        begin
        Call(tree,number);
i=1; refers to the root node being the current node at the beginning
        For(j=first_child_node;j<=last_child_node;next_child,j++)
         {
        If exist_edge(current_node,childi)
         { Crrent_array[i]=current_node_informationi;
```

```
        Child_array[j]=child_node_information_j;}
    }
        i++;
}
End.
```
(3) build_calculation_path(parent_node,child_node): Get the information of the parent node and child nodes orderly from Crrent_array and Child_array to form the calculation path based the algorithm listed above, then we can achieve the success probability of every path.

4.2 Next_Obj_Pro(t,t+1,n) Algroithm

This part aims to calculate transfer path success probability from current node (parent node) to next possible object (child node). In monitoring DHCI, operators' monitoring transfer is influenced by relevant information of DHCI and monitoring manipulation, so it could be assumed that operator's monitoring is data-driven. If licensed operators have had enough knowledge to monitor, it can be concluded that the next monitoring state generally only relates to the current monitoring state, and that the monitoring transfers merely base on the current information, so operators' monitoring transferring has strong Markov property.

It is generally acknowledged that Markov consists of quadruples (X, A, P, R) , where X stands for states set, A for paths set, P for transfer probability between two states, R for expectation value[7]. The mathematical formulation of Markov is[8,9]: as to any integer n and any extraneous variable xi, if:

$$P\ (X_1 = x_{i1} , X_2 = x_{i2} , \cdots, X_n = x_{im}) > 0 \qquad (1)$$

then,

$$P\ (X_{n+1} = x_{in+1} \mid X_1 = x_{i1} , X_2 = x_{i2} , \cdots, X_n = x_{in}) = P\ (Xn+1 = x_{in+1} \mid X_n = x_{in}) \qquad (2)$$

As to the transfer way from current state to the next, there are only two factors considered in this paper: one is the task information state, while the other is the decision process of operators. Transfer successful or not is decided by these two factors. So it is consistent with Multiplication Principle of probability theory, the transfer path error probability can be defined as:

$$failure\_Tranfer\_path\_probility(t,t+1)=P(rask_{t+1}|rask_t,rask_{t-1}, \cdots,rask_1)*p(task_{t+1}|decision_t,$$
$$decision_{t-1, }\cdots,decision_1) \qquad (3)$$

Where raskt is the current task information state at time t, raskt+1 is the information of possible task at time t+1, decisiont is decision process of the operators' selecting the path in monitoring. Eq. (3) indicates that the transfer process is mainly affected by current task state and operators' decision upon selecting the path in monitoring. The current task state reveals the physical properties of the system at that moment, while decision of selecting path is about the operators' mental activities. According to Eq. (2), we find that the transfer-influenced factors at time t+1 are only concerned with factors at time t, so Eq. (3) can be simplified as:

$$failure\_Tranfer\_path\_probility(t,t+1)=P(rask_{t+1}|rask_t)*p(task_{t+1}|decision_t) \qquad (4)$$

thus the transfer path success probability is:

$$Succ\_Tranfer\_path\_probility(t,t+1)=1- P(rask_{t+1}|rask_t)*p(task_{t+1}|decision_t) \qquad (5)$$

How to calculate the success probability according to Eq.(5)? We can see from Eq.(5) that if we know the methods to calculate $P(rask_{t+1}|rask_t)$ and $p(task_{t+1}|decision_t)$, we can easily get the value. So we will discuss their calculations followed.

(1)$P(rask_{t+1}|rask_t)$ Algroithm

As mentioned in the previous analysis, p(taskt+1|decisiont) refers to the error probability caused by the transfer process of task information state from time t to time t+1, Δt denotes the time space between two states, in terms of relevant study[2], the error probability of Δt is obtained:

$$\begin{pmatrix} p(task_i(t) = 0) \\ p(task_i(t) = 1) \end{pmatrix} = \begin{pmatrix} e^{-F_P(t)\Delta t} & 0 \\ e^{F_P(t)\Delta t} - 1 & 1 \end{pmatrix} \begin{pmatrix} p(task_i(t-1) = 0) \\ p(task_i(t-1) = 1) \end{pmatrix} \qquad (6)$$

Where taski(t)=0 denotes the current normal state, taski(t)=1 the current abnormal state, while F_p(t) the monitoring error probability of taski(t).

For convenience of calculation, Eq. (6) can be simplified as listed in Fig.1.

Table 1 Calculation formulae of transferring failure ratio between two consecutive states

P{ task$_j$(t)| task$_j$(t-1) }		task$_j$(t-1)	
	0	0	1
task$_j$(t)		$e^{-FP(t)\Delta t}$	0
	1	$e^{Fp(t)\Delta t}-1$	1

(2)p(task$_{t+1}$|decision$_t$) Alogroithm

The term p(task$_{t+1}$|decision$_t$) refers that the operators' monitoring transfer to next object depends on operators' current decision error, namely, the value is the error probability at time t, so, p(task$_{t+1}$|decision$_t$) and p(decision$_t$) are mathematically equivalent, that is:

$$p(task_{t+1} \mid decision_t) \Leftrightarrow p(decision_t) \qquad (7)$$

The decision process is decisive to transfer in that decision error will consequently lead to transfer error and this process is mainly influenced by the physical properties of task information and operators' individual factors. This decision process influenced by multi-factors can be simplified as[7]:

$$P(decision_t)=P(decision_t|task\ character,\ human\_factors) \qquad (8)$$

Actually, Eq. (8) is a calculation under multi-conditions. According to relevant studies[7], the conditional probability with many parent nodes can be solved by conditional probability with single parent node, and the expressions are listed below:

$$P(n = S_{N_i} \mid M_1 = S_{M_1,P_1,} M_2 = S_{M_2,P_2,} ...... M_K = S_{M_K,P_K,}) = \lambda \sum (\prod_{j=1}^{j=k} P(N = S_{N_i,} \mid M_j = S_{M_j,P_{i,}})) \qquad (9)$$

Where, $\lambda = \sum_{i=1}^{n} P(N = S_{N_i} \mid M_1 = S_{M_1,P_1}, M_2 = S_{M_2,P_2} ...... M_K = S_{M_K,P_K}$

How to judge whether a factor could be the decision influencing factor? Based on the author's study and experience in NPPs, analysis of the interviews with the operators, other experts' studies and the characteristics of this research itself [10,11,12,13], we conclude 6 factors being taken into consideration (Table 2).

Table 2 The correlation factors that influence operators' decision

affecting factors	Variables	affecting factors	Variables
Operators' knowledge and experience	d1	Operators' training level	d2
Task complexity	d3	Decision support system	d4
Stress level	d5	Time stress	d6

Toward to the factors in Table 2, combine Eqs. (8) and (9), then the further derivation expression of P(decisiont) is as following:

$$p(decision_t) = \sum_{i=1}^{i=6} [\sum (\prod_{j=1}^{k} p\ (decision_t \mid d_j))] \qquad (10)$$

Where i refers to the factor count, j refers to the state of factors.

5 CASE STUDY

This paper take SGTR accident of NNP as an example and its 3K00118YMA DHCI as the information source node at time t in the monitoring process. The laboratory equipments used in the experiment are eye tracking system (Tobii), virtual workstation, and accident simulation screen(developed by soft Visual studio.net). In terms of the FPDP method constructed above, the specific process in this case are:

(1) Build_tree(n)：set up tree structure of the monitoring path based on FPDP method;

(2) Take the DHCI of 3K00118YMA as the initial monitoring object at time t;

 (3) According to Search(tree,relative_edge) algorithm, find out all of child nodes screen to the parent node screen(3K00118YMA) from the monitoring path tree of SGTR, then the parent node screen and the next possible child node screens will be obtained (Fig.2).
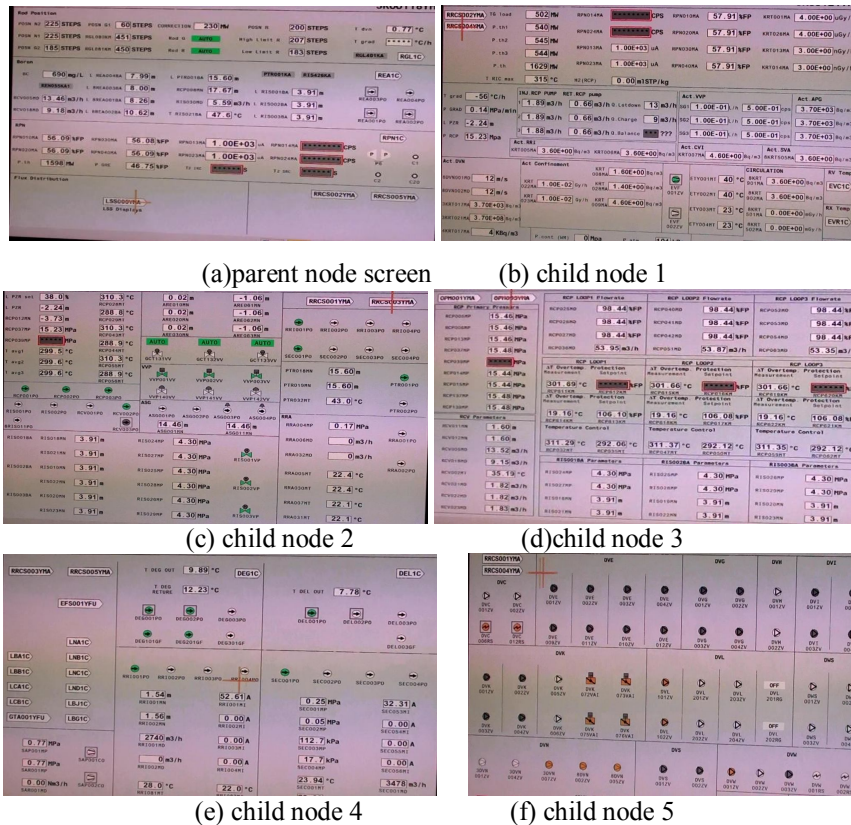

(a)parent node screen   (b) child node 1

(c) child node 2   (d)child node 3

(e) child node 4   (f) child node 5

Fig.2 The father node and its child nodes selected in SGTR accident

(4) Get the tree structure of the parent node and the child nodes according to build_calculation_path(parent_node,child_node) (Fig.3).
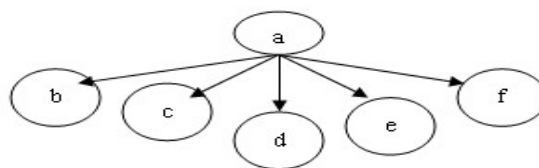

Fig.3 The father node and its child nodes selected in SGTR accident

Where the letter a in Fig.3 stands for the screen (a) in Fig2, in a similar way, letter b stands for screen (b) in Fig.2, ect.

(5)Next_Obj_Pro(t,t+1,n) algroithm

For ease of description, the transfer path success probability is separated into 2 parts: P(raskt+1|raskt) and P(decisiont). The follows are the respective calculations of them:

P(raskt+1|raskt) algroithm

When accident happens, the current task state and the next task state are abnormal, Eq. (12) can be obtained according to Table 1:

$$p(task_j(t) \,|\, task_j(t-1)) = e^{F_p(t)\Delta t} - 1 \qquad (12)$$

Parameters of parent node and each child node are obtained by experimental analysis and listed in Table 3:

Table 3 Parameter values of parent node and some child nodes obtained from experiment

$a \rightarrow b$		$a \rightarrow c$		$a \rightarrow d$		$a \rightarrow e$		$a \rightarrow f$	
$F_p(t)$	Δt	$F_p(t)$	Δt	$F_p(t)$	Δt	$F_p(t)$	Δt	$F_p(t)$	Δt
0.0008	29	0.0001	20	0.005	47	0.003	39	0.001	35

We can obtain the P(raskt+1|raskt) value of node pair (the parent node with a child node) according to Eq. (12) and Table 3(See Table 4).

Table 4 The results of the $P(rask_{t+1}|rask_t)$ value of node pair (the parent node with a child node)

Transferring path	$a \rightarrow b$	$a \rightarrow c$	$a \rightarrow d$	$a \rightarrow e$	$a \rightarrow f$
$P(rask_{t+1}|rask_t)$	0.023	0.002	0.265	0.124	0.035

① P(decision$_t$) algroithm

Among the 6 decision affecting factors in Table 2, d1,d2,d5 and d6 are unrelated to the execution of the task but to the operators' themselves, that is, though it is irrelevant to the path, there would be different states for them in monitoring. In terms of [9] and [14], we can achieve the values of d1,d2,d5and d6 of different states, Table 5 can be obtained based on Eq. (8).

Table 5 The error probability of factor d1,d2,d5and d6, and their sum of products of different state

d_1			j=1	j=2	j=3		d_2	j=1	j=2	j=3
			0.25	0.002	0.001			0.01	0.02	0.001
Decision	j=1	0.1	0.025	0.00004	0.00001			0.003	0.0004	0.00003
	j=2	0.02	$P(decision/d_1)= 0.02505$					$P(decision//d_2)= 0.00343$		
	j=3	0.01								
d_5			j=1	j=2	j=3		d_6	j=1	j=2	j=3
			0.03	0.01	0.003			1.0	0.1	0.01
Decision	j=1	0.1	0.003	0.0002	0.00003			0.1	0.002	0.0001
	j=2	0.02	$P(decision//d_5)= 0.00323$					$P(decision//d_6)= 0.1021$		
	j=3	0.01								

Note: j=1,2,3 refers to the state bejing high, middle and low.

According to the actual situation, factor d3 and d4 only have one sort of state, but their values vary with DHCI. Combined with expert judgment and actual experience in NPP, the values can be obtained in accordance with different transfer paths, the results are listed in Table 6 as follows:

Table 6 The error probability of factor d3 and d4 in different paths

Transferring path	$a \rightarrow b$	$a \rightarrow c$	$a \rightarrow d$	$a \rightarrow e$	$a \rightarrow f$
$P(decision/d_3)$	0.06	0.001	0.9	0.6	0.2
$P(decision/d_4)$	0.001	0.005	0.1	0.08	0.04

In accordance with Table 5, Table 6 and Eq. (11), the values of P(decision$_t$) of each transfer are listed in Table 7.

Table 7 The error probability of P(decision$_t$)

Transferring path	$a \rightarrow b$	$a \rightarrow c$	$a \rightarrow d$	$a \rightarrow e$	$a \rightarrow f$
$P(decision_t)$	0.1948	0.13981	1.13381	0.8138	0.3738

③ The results of Succ_Tranfer_path_probility(t,t+1)
Based on Tables 4 and 7, Eq. (5), the success probability of each path is listed in Table 8:

Table 8 The successful probability of each transferring path

Transferring path	$a \rightarrow b$	$a \rightarrow c$	$a \rightarrow d$	$a \rightarrow e$	$a \rightarrow f$
Succ_Tranfer_path_probility(t,t+1)	0.996	0.998	0.7	0.899	0.987

(6)Max(t+1,n)
Select the maximum transfer probability from Table 8, we can find that the maximum is 0.998.
(7)Transfer_route(t+1)
Based on step (6), we can know that the next transfer path would be（a）→（c）, that is, the parent node screen (a) transfers to the child node screen (c)(child node screen 2 in Fig.2)
(8)END().
According to the FPDP method for DHCI of NPP proposed in this paper, operator's transfer path was obtained successfully through monitoring 3K00118YMA in the SGTR accident. The forecasting result is in consistent with path transferring (frame (a) transfers to the frame (c) in Fig.2) of responding manipulation instruction given by operators in an actual SGTR accident of a NPP, as well as the transferring path achieved by video investigation and eye tracking system analysis when operators handle with SGTR accident in simulator. Therefore, the FPDP algorithm proposed in this paper is available.

6 CONCLUSION

This paper proposed FPDP method for the monitoring transferring process of DHCI of NPPs, which consists of plan mode, execution flow and key algorithm and so on. Then, the method is applied to analyze SGTR accident of digital NPP and the predicted monitoring transferring path which is consistent with actual situation. Thus the method proposed herein does helpful to decrease operator's monitoring errors, which will also contributes to analyze the driving mechanism of operators' monitoring activities, to train simulated for monitoring behavior, to optimize the digital man-machine interface, to analyze the monitoring behavior on other fields: radar, intelligent robot, aerospace, and so on.
However, there exists some limitations as to this method, for example, we only select 6 factors that influences operators' decision, undoubtedly, there are more than 6 factors that would influence decision; also the value of the factors adopted from the existed data or experts judgments; meanwhile, the formation of the tree structure still need improving to reduce the complexity of inquiry.

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