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A graphic modeling and analysis tool for human fault diagnosis tasks

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Abstract

This study presents a graphic modeling and analysis tool for use in constructing an operator's mental model in fault diagnosis tasks. In most automatic and complicated process control systems, human fault diagnosis tasks have become increasingly complex and specialized. The system designer should consider the cognitive process of human operator to avert failure of implement action owing to a lack of compatibility between humans and aiding system interface. Here, an experiment is performed to investigate the nature of human fault diagnosis. A graphic modeling and analysis tool is then proposed to model the continuous process of human fault diagnosis. The approach proposed herein exploits both the line-chart and Petri nets to demonstrate the operator's thoughts and actions. Moreover, results in this study are integrated into an adaptive standard diagnosis model that can assess the operators' mental workload and accurately depict the interactions between human operator and aiding system.

Relevance to industry

Automatic intelligent diagnosis systems can not provide satisfactory operating performance. Human diagnosticians are more effective than computer ones. Results in this study offer further insight into an operator behavior in graphic form and also how to design a better aiding system. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Fault diagnosis; Mental model; Petri nets

1. Introduction

Fault diagnosis is a prerequisite in automation systems from the perspectives of factory safety and manufacturing cost. Individuals in a supervisory control system serve as a backup in the case of a failure in automation of a process plant unanticipated situations (Annemarie Sassen et al., 1994). Diagnosticians exercise a high level of mental activity because they are the final authorities in taking appropriate actions to avoid or to recover from system failures. Moreover, the operator experiences

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a tremendous amount of temporal stress. Under above circumstances, the likelihood for making decision errors is high (Sheridan and Hennesy, 1984). Despite artificial intelligence related efforts to develop an automated intelligent diagnosis system (Abbott, 1988; Davis, 1984; Genesereth, 1984), fault diagnosis still remains one of the tasks that humans excel a computer (Sheridan, 1981; Chen, 1990). Therefore, a support system should be developed that would (a) assist a diagnostician in unforeseen circumstances and (b) release the operator from temporal constraints and direct him/her to those tasks at which he/she excels.

However, the effects of introducing an assist approach cannot accurately predict the changes in operator performance during fault diagnosis. On the one hand, the performance may be improved since such assistance may (a) allow the operator to detect and diagnose faults quicker and more accurate and (b) release the operator from temporal constraints. On the other hand, performance may worsen in terms of underloading the operators' mental workload or bad aid design (Wen and Hwang, 1994; Stassen et al., 1990).

Evaluating the diagnostician's performance, requires closely examining the user behaviour. Baecker and Buxton (1987) proposed that users' mental models and performance are "intimately linked". Yoon and Hammer (1988) recommended that the aiding information should be compatible with a human's information process. More throughly understanding the strategies used by humans and the difficulties they may encounter facilitates the development of training and aiding methods to assist human operators in fault diagnosis tasks (Lin, 1993). From the perspective of human information processing, human diagnostic activity should be analyzed before designing a successful information aid.

Cognitive ergonomics is oriented towards optimizing human–machine systems, under the following criteria: characteristics of human cognitive processes, software science knowledge, and knowledge in diverse work domain technologies (Green and Hoc, 1991). The cognitive scientist's perennation allows for an optimal situation to be reached. However, constructing an individual mental model is quite time consuming. Also, a possibility in which user models can be constructed in an automatic, bottom-up approach to assist cognitive ergonomic scientist would make modeling and analyzing easy, productive and valid in an empirical sense (Rauterberg, 1993).

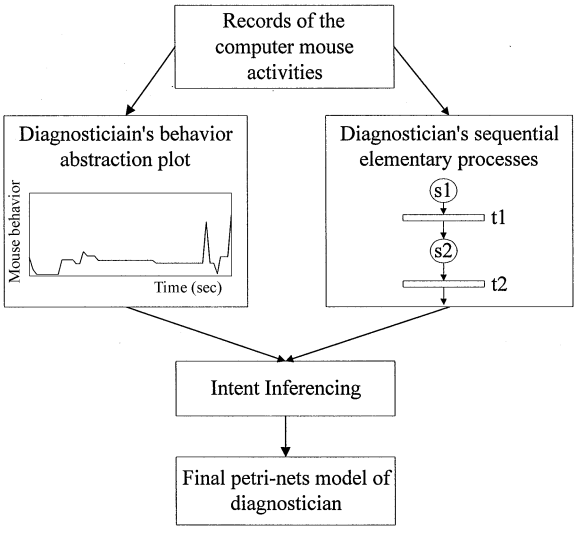

Fig. 1. The conceptual diagram of automatic modeling and analysis tool.

This work presents a graphic modeling and analysis tool (GMAT), capable of modelling and analyzing the continuous process of human fault diagnosis. GMAT can describe models in both quantitative and qualitative forms. In particular, the proposed approach exploits both diagnosis abstraction plot (DAP) and time Petri nets (TPNs) to demonstrate the operators' thoughts and actions. Fig. 1 depicts the approach.

2. Background

The user must construct a mental representation of the system's structure and obtain knowledge about the functions of this system with respect to a set of tasks. Furthermore, he/she must learn a 'language', i.e., a set of symbols, syntax, and operations to evoke interaction sequences (the interactive 'process') related to tasks and subtask functions (Rauterberg, 1993). Therefore, knowledge

Table 1
Knowledge elicitation methods

Manual	Automatic
Interview	Induction
Questionnaire	Repertory grid
Protocol analysis	

elicitation is the initial step of constructing an operator's mental model.

2.1. Methods of knowledge elicitation

Many expert systems have been developed by manual or automatic knowledge elicitation methods (Chao and Salvendy, 1995). Table 1 summarizes those methods, with each separately discussed as follows:

- Manual methods – interview, questionnaire or protocal analysis method
  Interview is the conventional means of obtaining knowledge from a human expert (Tuthill, 1990).
  Questionnaire is "an ordered arrangement of items...intented to elicit the evaluations, judgement, comparisons, attitudes, beliefs or opinions of personnel...A visual mode of presenting the item is employed...items can also be presented by closed circuit television on a cathode ray tube (CRT) or on a video display terminal (VDT) under the control of a computer program (Babbitt and Nystrom, 1985)."
  Protocal analysis method requires the experts to 'think aloud' while performing a task or solving a problem (Tuthill, 1990; Bainbridge, 1979; Hoffman, 1987; Neale, 1988)
- Automatic method – induction or repertory grid method.
  Induction extracts knowledge from examples. An inductive software can be used to acquire knowledge by deriving the rules from examples. PRISM (Cendrowska, 1988) employs this method.
  Repertory grid method is derived from Kelly's (1955) person construct theory. A repertory grid uses identified elements and constructs to describe objects. A construct is a bipolar characteristic representing the degree of each element, and the element is what an expert considers. It is a two-way classification of data. The mapping of the elements onto the constructs produces the two-dimensional grid of relationships (Shaw and Gaines, 1987).

2.2. Measurements of cognition

Several methods have been applied to measure cognitions, including questionnaires (Scott et al., 1979), ratings of observable behaviour (e.g., 'scoring rationales', McDaniel and Lawrence, 1990), protocol analysis (Ericsson and Simon, 1984), and formal models (Kieras and Polson, 1985).

Rasmussen (1986) contended that at least two different forms of mental models must be considered: a mental model used in commonsense reasoning in terms of interacting objects and a more formal model in terms of variables and relations.

Among the several formalisms for constructing user models include MAD (Scapin and Pierret, 1990), TAG (Payne and Green, 1986), CLG (Moran), CCT (Kieras and Polson, 1985), GOMS (Card et al., 1983), and BNF (Reisner, 1981). By using any of these formalisms, the investigator cannot only categorize user behavior according to the chosen model, but also design the more or less pure user model in a top-down approach. The investigator can then attempt to test his/her model with empirical data, which must be cleaned up before testing to become more or less 'error free' (e.g., Churchill, 1992). This task is often difficult and relies on the expressive power of the used formalism. Rauterberg (1993, 1995) presented an automatic mental model evaluation (AMME) which uses Petri nets to construct a user model in an automatic, bottom-up approach. AMME, although capable of tracing user behavior in a finite and discrete state space, has difficulty in tracing operator's behavior in the fault diagnosis task which is a continuous process.

Information technology heavily influences some model that do not heavily emphasize the data from field studies. For instance, cognitive environment simulation (CES) is based on Caduceus diagnositic system (Woods et al., 1987) and operator function

models expert system (OFMspert) implemented in a blackboard architecture (Rubin et al., 1988). Both systems are sustained by cognitive theories and are oriented toward decision support systems for a simulated dynamic environment. Other models are based on data from actual situations. A notable example is a cognitive simulation model (COSIMO), which simulates an operator's behavior in controlling a complex system during the management of accidents (Cacciabue et al., 1992).

3. The process and the control room

3.1. The heat transfer salt system of the melamine plant

As Fig. 2 depicts, the heat transfer system contains typical operations of process plants. The diagram of a simulated system is designed according to the display on the control console in a real plant. The endothermic reaction heat is obtained by the combustion of fuel gas in a furnace. In the furnace, heat is transferred to circulating salt mixture which, subsequently, delivers this heat to the reactor. The salt's composition is $NaNO_2$, $NaNO_3$, and KNO_3. Under normal operating condition, the salt tank contains a salt melt of 410°C, which is passed through the coils of the furnace by a submerged pump. Fuel gas is fired in the bottom of the furnace. The hot combustion gases brush past the salt coils, and transfer their heat to the salt. Next, the salt leaving the furnace at a temperature of 430–440°C (measured by TIC indicator) is fed to the coils of the reactor. The coils inside the reactor are divided into three sections. Some heat is absorbed by urea, reaction substance; the salt, having been cooled to 410°C, descends to the salt tank. In this manner, the salt's temperature in the reactor is maintained at the optimal range of 380–385°C.

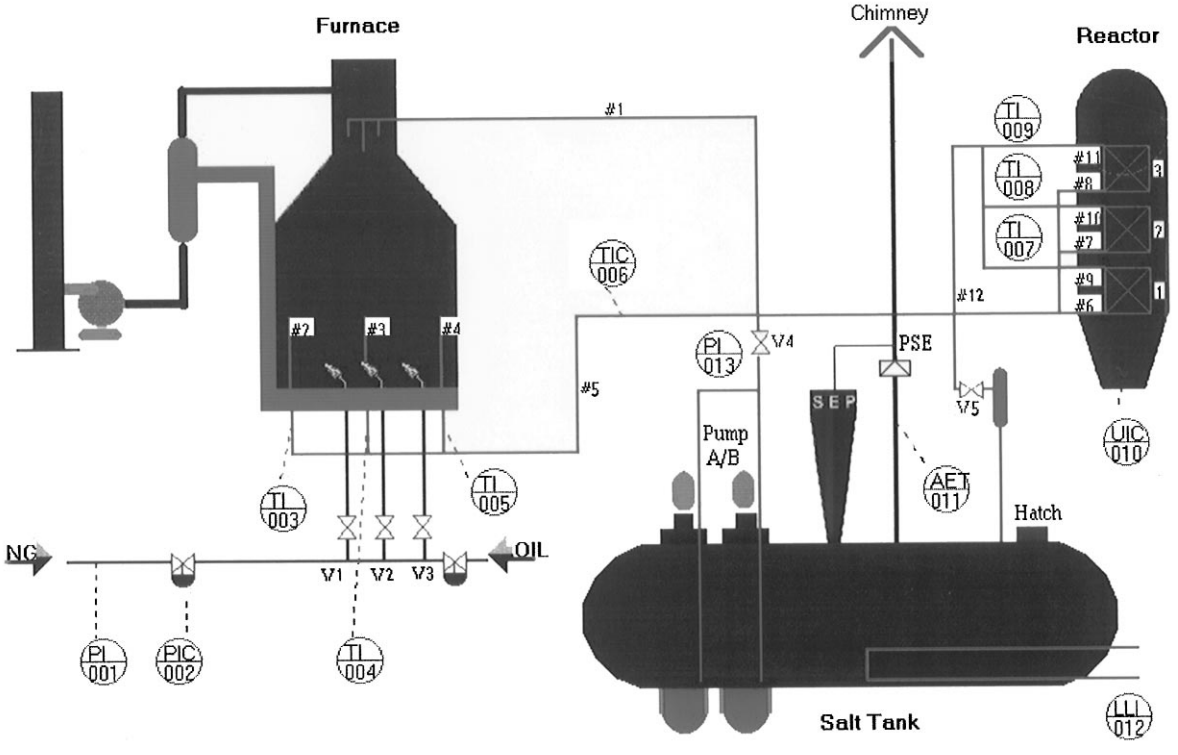

Fig. 2. The simulated heat transfer salt system of the melamine plant.

3.2. The human–computer interface

In this experiment, 13 sensors provide the dynamic information about the system's states; that information is updated every 5 s. The instrumental display consists of the alarm information, such as blue alarm denotes low, and red alarm denotes high. Regarding to the actual system, the trends in each instruments are displayed dynamically on the diagram of the simulated subsystem.

4. Graphic modeling and analysis tool (GMAT)

4.1. The basic concept

GMAT design is based on intent inferencing. An intend inferencer attempts to plausibly explanation for observed operator actions given the current system state and past operator actions within the context of a normative model of the operator. Intent inferencing provides the understanding properties necessary for an intelligent operator's associate (Geddes, 1986; Rubin et al., 1987). Understanding an operator's actions in this context is analogous to understanding actions in the theory of goal-directed behavior and planning. This theory contends that actions are understood when identified as part of a sequence of actions undertaken in the realization of a goal (Card et al., 1983A; Hayes-Roth, 1985). "Thus, understanding a situation involves inferring, goals, plans, and actions ⋯ and relating these items to each other as well as other aspects of the situation (Erman et al., 1980)." Thus, knowing the overall intent of an action is the same as understanding the actions.

The user's mental model can be developed in representing objects, operations, states, system structure and task structure (Rauterberg, 1993). The following two sections describe how to represent the operator's intentions in detail. In complex and dynamic systems, however, the mouse has become a common input device for a window-based control system. Therefore, both mouse movement and click motion are used herein to construct actions diagram so that an operator's intentions are accurately represented.

4.2. Theoretical foundation of GMAT

In GMAT, diagnosis abstraction plot (DAP) and timed Petri nets (TPNs) are used to achieve the goal. Each foundation of these methods is described as follows.

4.2.1. Diagnosis abstraction plot

A problem-solving model is a scheme for organizing reasoning steps and domain knowledge to construct a solution to a problem. The central issues in any problem-solving model are "What pieces of knowledge should be applied?" and "when and how should they be applied?" (Nii, 1985). The blackboard model answers these questions by separating the problem-solving framework into three major components: knowledge source, blackboard control, and blackboard data structure (Nii, 1985). To adequately perform intent inferencing, two major activities must occur: (a) construct the representation of operator's current state. This representation involves the operator's current locations and actions; (b) explain the representation. During an abnormal situation within a plant, operators carefully examine the information in the trend diagrams periodically. An extremely useful graphical representation of the operator actions by DAP is shown in Fig. 3. DAP is created by plotting the time against occurences of operator actions. The Y-axis, denoting occurences of operator actions, contains the block numbers which are the cursor positions and click numbers which are the clicks of mouse. The screen is divided into a 8×10 matrix where each block represents the corresponding cursor position. The peak appearing in Fig. 3 represents the mouse click that is just the block number where mouse being plus 100. For instance, when the mouse is moved to block 1 (block number = 1) and is clicked (click number = 101).

4.2.2. Recognition of DAP

The DAP patterns, however, would be recognized into some kinds of different presentation forms which denote the different diagnostic strategies, as suggested herein. Reviewing the diagnosis models can hopefully clue us to identify the DAP patterns. Rasmussen (1981) divided the fault diagnosis strategies into topographic search and

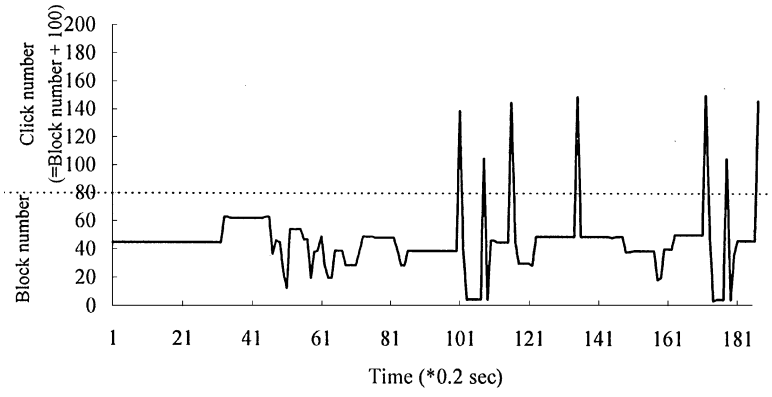

Fig. 3. Diagnosis abstraction plot.

symptomatic search. Yoon and Hammer (1988) presented a deep-reasoning model for fault diagnosis tasks. Their model assumed that humans would gradually collect the relevant information about an abnormal situation from the possible causes in the initial stage of diagnosis: this is called data-driven search. Next, as the effectiveness of data-driven search decrease, the hypothesis-driven search might be used as an alternative. Konradt (1995) indicated that the typical strategies of failure diagnosis are historical information, least effort, reconstruction, and sensory check. In addition, symptomatic search and topographic search are frequently used in case-based strategies, particularly in routine diagnosis tasks.

4.2.3. Timed petri nets (TPNs)

Given a finite action space, each state corresponds to a system context, and each transition corresponds to a system operation. A trace/sequence of states and transitions in this action space can describe a complete problem-solving procedure. Each finite trace/sequence in the action space is called a process. An overall diagnostic procedure contains two different kinds of information: (1) information processing tasks, i.e. the diagnostic subprocedures that can be characterized by their input, output, and processing; and (2) the control strategy, i.e. the means to select information processing tasks.

Finite state transition nets can be completely described with Petri nets, which have a clear semantic form (Peterson, 1981). Timed Petri nets, a graphical modeling tool, has been extensively used to model, analyze and evaluate of discrete event systems (Ajmone, 1989; Murate, 1989; Zuberek, 1991). From the modeling perspective, interactive relations among the processes, resource and time delays can be concisely and formally described by TPNs. Timed Petri nets is formally defined as follows:

$P = \{p_1, p_2, \Lambda, p_n\}$ is a set of places, where n denotes the number of places;

$T = \{t_1, t_2, \Lambda, t_m\}$ is a set of transitions, where m denotes the number of transitions;

$I : (P \times T) \to N$ denotes an input function that defines the number of directed arcs from places to transitions, and $N = \{0, 1, 2, 3, \Lambda\}$;

$O : (P \times T) \to N$ represents an output function that defines the number of directed arcs from transitions to places;

$M : P \to N$ is a mark function indicating the number of tokens in each place. Tokens are indicators in places which represent the number of available resources or the number of the accumulated entities.

Fig. 4 depicts the simplex TPNs, where the circle denotes the place and the bar symbolizes the transition. Also, arcs represents the relations between place and transition.

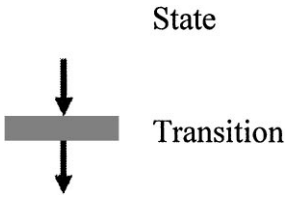

Fig. 4. The simplex timed Petri nets.

5. Methodology

The observation of operators performing the fault diagnosis tasks is the fundamental data collection. Qualitative and quantitative analyses are considered herein. In qualitative analysis, a graphic feature of the complete diagnosis task, DAP explains the diagnostic procedure, in which the behavior of individual processes is traced. In quantitative analysis, each observed diagnostic procedure can be quantified with four measures by TPNs: diagnosis time (DT), test times (TT), the number of behavior transitions (BT), and the number of behavior states (BS).

5.1. Experiment

Twelve undergraduate students at Tsinghua University (Hsinchu, Taiwan) voluntarily participated in this experiment. All the subjects had taken at least one fundamental chemical course. The subjects, who were inexperienced in diagnosing the simulation system, were trained before the experiment.

During the experiment, each subject diagnosed faults in twelve different fault scenarios as precisely and as quickly as possible. The fault scenarios comprised of nine single and three multiple faults scenarios. Each subject monitored and diagnosed 12 scenarios. However, the order in which they presented was random for each subject to balance learning effects.

The subject's behaviors were recorded by a computer to avoid interruption with the diagnostic process. The experimental facilities included one Super Pointer mouse and two Pentium 586-120 personal computers: one simulated the heat transfer salt system of the melamine plant system, and another was used to record the mouse coordinates and clicks. For recording the equal cursor position, two computers were connected with the same mouse.

5.2. Quantitative analysis

An aid approach offers the operator higher performance in diagnosing faults, such as training, automatic diagnosis and an assistant system (Wen and Hwang, 1994). As expected, the operator more accurately diagnose the faults with less diagnosis time. Herein, four indices are used to indicate the operator performance. First index is the total time that a subject spends to diagnose a fault scenario. Second index is the frequency of an incorrect diagnosis made by the subject during a scenario. In single fault scenarios, whether a subject's diagnosis is correct or not can be clearly identified. In a multiple fault scenario, the entire diagnosis is incomplete untill a subject has identified all malfunctions. Third index is the number of different state of subject's behavior in a scenario. The subject's behavior includes all information process tasks such as symptomatic search, data-driven search, and hypothesis-driven search. Fourth index is the number of different transitions of a subject's behavior during a scenario. As the subject faces an unfamiliar malfunction, one can expect that the number of transitions of subject's behaviour will be increased (when the subject attempts to check every component) or decreased (when the subject reviews the system manual or makes a decision).

5.3. Qualitative analysis

In constructing the DAP recognition system, the diagnosis strategies from previous literature were complied. The overall diagnostic procedure can be viewed as a combination of two stages: information processing tasks and a control strategy (Wen and Hwang, 1994; Lin, 1993; Yoon and Hammer, 1988). Information processing tasks are diagnostic subprocedures that can be characterized by their input, output, and processing. Those tasks comprise of data-driven search, symptomatic search, hypothesis-driven search, topographic search, intuition, decision making, and testing.

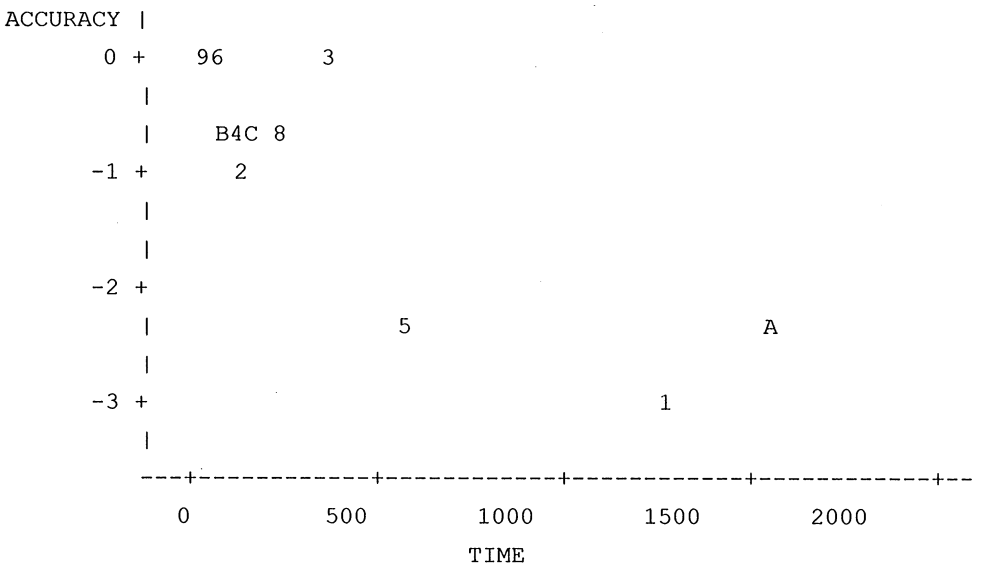

Fig. 5. The speed-accuracy operating characteristic of diagnostic performance in scenario 1. Note: 1 ~ 9: Subject 1 ~ Subject 9; A: Subject 10; B: Subject 11; C: Subject 12; Subject 7 is hidden behind Subject 4.

Control strategy is the means by which information processing tasks are selected. Although the control strategy is difficult to identify, this study uses the behavior transitions of TPNs to account for how the information processing tasks are switched during a fault scenario.

6. Results

Typically, the decision process is sequential (Payne, 1980). Once an initial hypothesis is formulated, further evidence is sought to confirm or refute it. Sequential process is particularly typical in troubleshooting or fault diagnosis when it is somewhat unlikely that a particular set of symptoms will instantly trigger a final diagnostic decision (Rasmussen, 1981). The operator's diagnosis strategies described in this section are based on the sequence of events generated by subjects using the mouse. This section provides several examples of how the operator's diagnosis strategies are represented by GMAT. As to the human performance, quantitively representing operator's strategies to diagnose faults, is a prerequisite to constructing the 'best' fault diagnosis model.

Table 2
Clusters of subjects for each scenario (1–9: subject 1–subject 9; A: subject 10; B: subject 11; C: subject 12)

Scenario	Cluster I Experts	Cluster II Advanced	Cluster III Novices
1	4, 7, 2, C, 6, B, 9, 8	3, 5	1, A
2	4, B, 7, A, C, 2, 8, 9	1, 6	3, 5
3	6, 9, 5, 3, B, 8, C	4, A, 7	1, 2
4	9, B	3, 4, 7, 8, 1, 6, 2, A	5, C
5	4, 9	2, 5, 3, 1, B, A, C, 8	6, 7
6	4, 7, 6, C, 2, 5, B	3, 9, 8, A	1
7	7, 9, 2, 8, 5, 3, B	1, 6, C	4, A
8	9, B, C	2, 6, 3, 4, 8, A	1, 5, 7
9	9, B, 3, 5, 2, 6	4, 8, 1, 7	A, C
10	1, 5, 2, 8, 9, 4, B	6, A	7, C, 3
11	7, 9, 4, 8, 5, B, 1, 6, C	2, A	3
12	8, C, 7, 2, 3, 4, B	1, 5, 6	9, A

6.1. The operator cluster analysis

Welford (1978) proposed that the strategies an operator may select to perform a task are relevant to workload because the operator may perform a task in a qualitatively different manner as the task difficulty increases. High performance in absolute judgement appears to correspond to professional experience with a particular sensory continuum in industrial task (Welford, 1968). Therefore, measuring performance is the initial step in understanding an operator's familiarity in fault diagnosis task. The differences among each operator who use their own diagnosis strategy can then be easily detected.

Individuals frequently make errors in reaction time tasks, and more so when responding quickly. A reciprocal relationship exists between latency and errors, referred to as the speed-accuracy tradeoff. The speed-accuracy operating characteristic, or SAOC, is a function that represents reaction time performance (Wicken, 1986). In SAOC, the performance of upper-left point exceeds that of lower right point. In this study, performance is defined in terms of two dimensions: diagnosis time and accuracy. The accuracy is expressed in terms of the measure $\log(1/TT)$. Fig. 5 presents an illustrative example of SAOC based on the data from twelve subjects in the scenario 1.

Based upon their performance level, the subjects were classified on the basis of cluster analysis in SAS as either novices, advanced, or experts in each scenario. Table 2 summarizes the clustered results for each scenario, in which clusters I, II, and III denotes experts, advanced, and novices, respectively.

6.2. The operator's diagnosis strategies

Alarms offer vital information for operators in process control systems. As a system's malfunctions increase, more alarms appear on the monitor. Notably, the different extents of malfunction in each of senarios force the operator to adopt different diagnostic strategies. The operator strategies described in this section are based on two sources of information: the sequence of events generated by a subject with a mouse and the cluster analysis results.

The overall procedure of fault diagnosis tasks can be divided into search stage and verification stage. Therefore, the strategy adopted by an operator in search stage is called search strategy. In

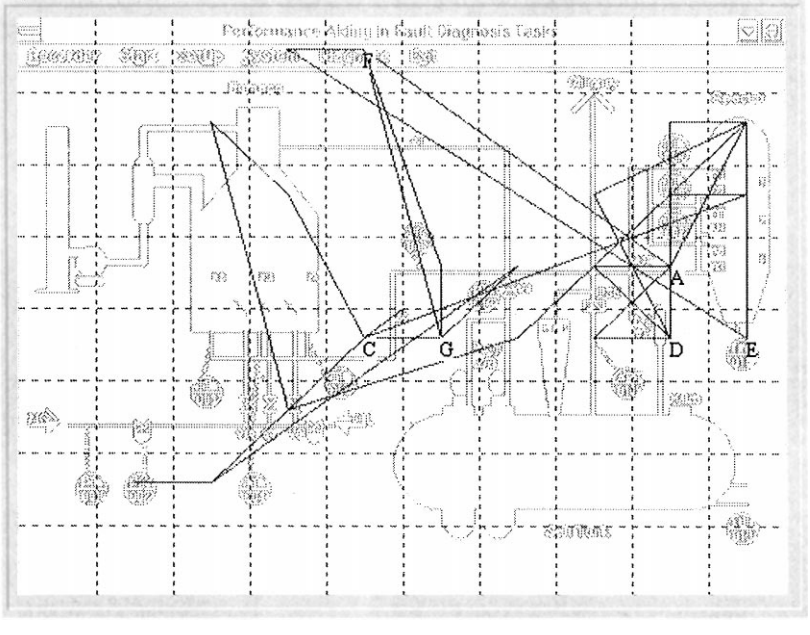

Fig. 6. Diagnostic track generated by Subject 11 who ran the third fault scenario.

addition, the strategy adopted by an operator in verification stage is called test strategy.

Fig. 6 displays the diagnostic track, indicating that the subject in the third senario, focused on the reactor most of the time. Fig. 7 summarizes the sequential events generated by subject 11 who ran the third senario. The circle on the left side reveals that the subject moved the mouse throughout the monitor to search for alarms or possible faults, and concentrated on the reactor. The circles at the medium and the right side indicate the sequential process of verification: hypotheses formed, tested, and confirmed.

In contrast, Fig. 8 tracks the same subject in the seventh scenario. The leftest 'decision making' denote that the subject fixed the mouse for a long time. This phenomenon implies that subject either waited for the important alarm to occur, or was new to the malfunction and scanned the system manual.

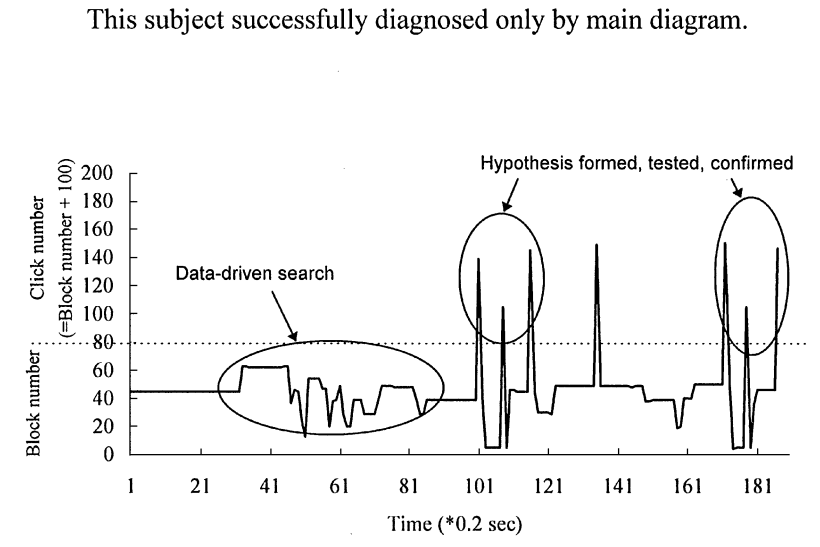

Fig. 7. DAP generated by Subject 11 who ran the third fault scenario.

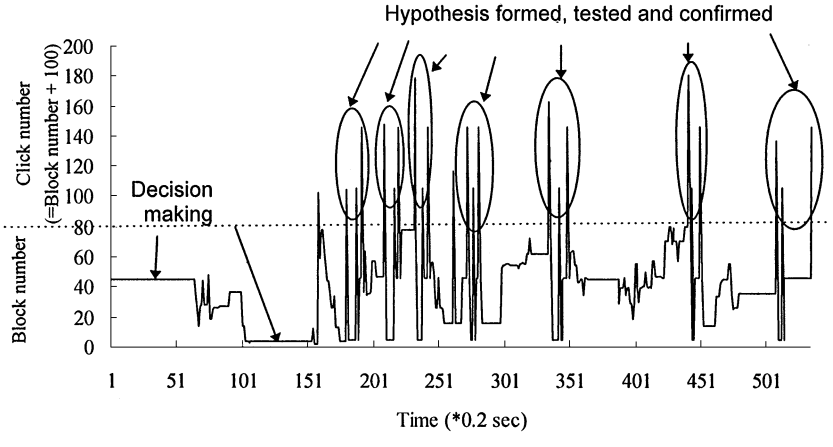

Fig. 8. DAP generated by Subject 11 who ran the seventh fault scenario.

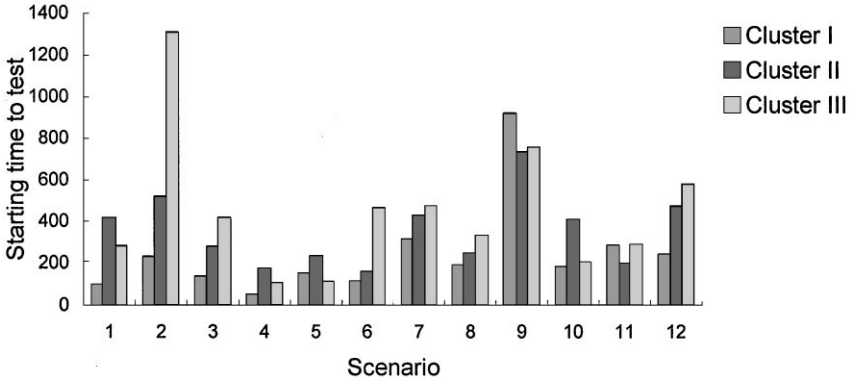

Fig. 9. The comparison of starting time to test for three clusters.

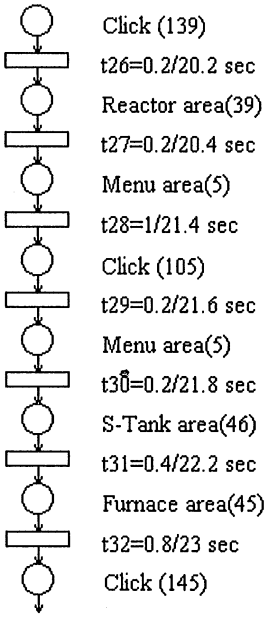

Fig. 10. The diagnostic part events of subject 11 who ran scenario 3.

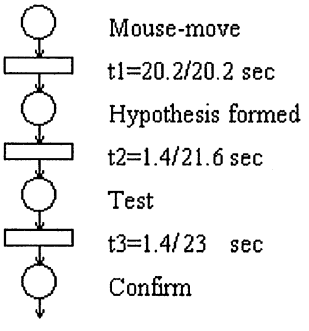

Fig. 11. Folded diagnostic behavior of Fig. 10.

Fig. 9 demonstrates that the subjects in cluster I started to test faster than cluster II and cluster III in all scenarios expect scenario 9. During scenario 9, no alarm was given, however, the temperature indicators fluctuated. Experimental results indicated that the subjects in cluster I were more conservative than those in clusters II and III during scenario 9. However, the subjects in cluster I might have adopted some search strategies to quickly generate the first hypothesis for diagnosing the faults.

6.3. Time Petri nets

An illustrative example of timed Petri nets in GMAT is present as follows. Fig. 10 illustrates that subject 11 performed part of the diagnostic events during scenario 3. In 20.2 s, this subject clicked on block 39 which belonged to the reactor area and made a hypothesis. Next, the subject moved the cursor to menu area and tested the hypothesis. In 23 s, this subject confirmed the hypothesis which he made. Fig. 11 depicts that the subject's folded diagnostic behavior of Fig. 10. In this example, the events were generated by subject 11 in the scenario 3. The total diagnosis time was 37.4 s, the number

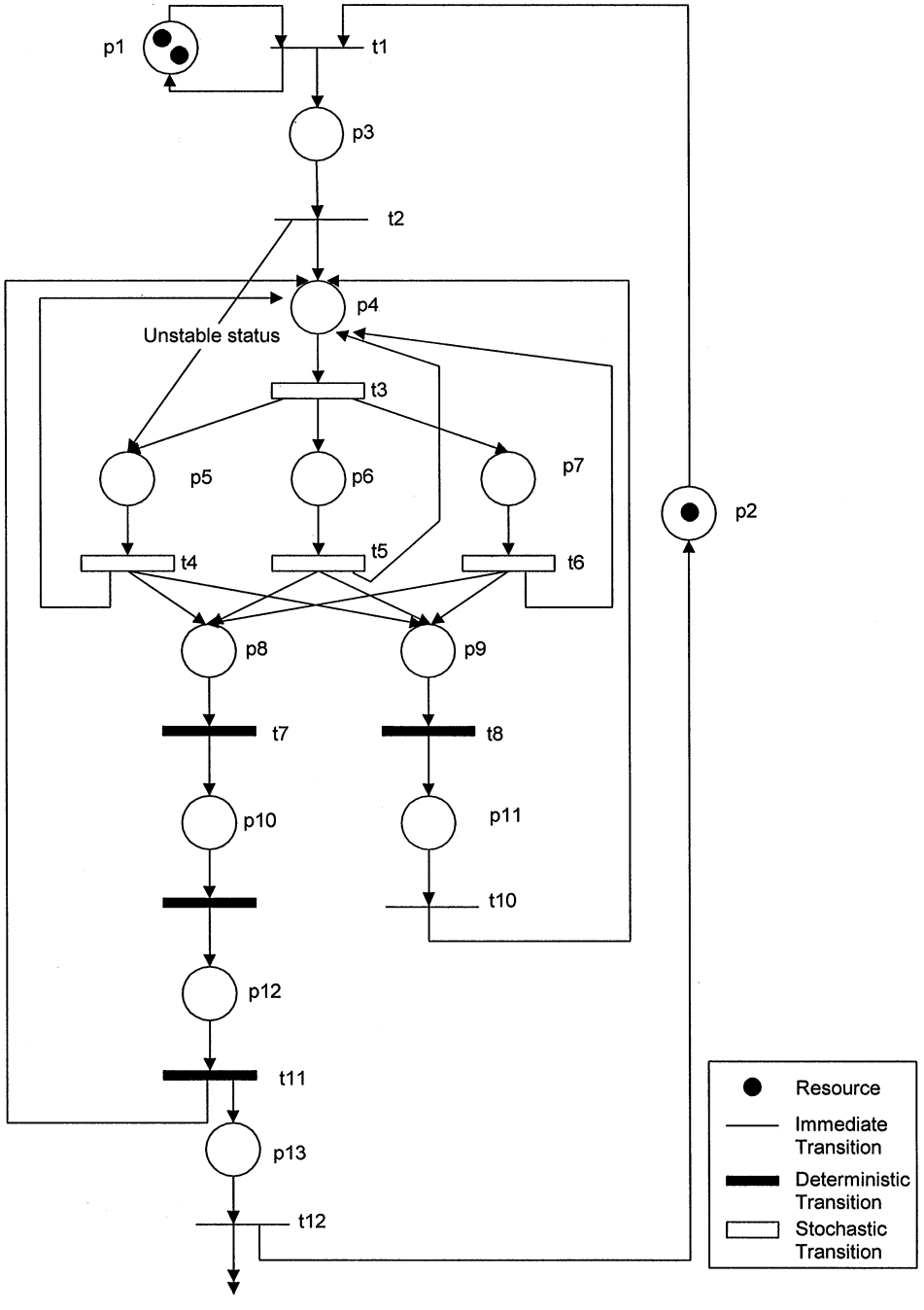

Fig. 12. The final Petri net model for fault diagnosis tasks.

of transitions was 56, the number of states was 56, and the number of tests was 2.

7. Discussion and conclusions

As Fig. 12 reveals, the experimental results are integrated into a final Petri net model for human fault diagnosis tasks. Table 3 displays an interpretation of the states and transitions. This model is based on the records of diagnostic behaviors. The final Petri net model, in contrast with other models of human diagnostic performance, attempts to describe the human diagnostic strategy in terms of a graphic model. Based on the results presented herein, we can conclude the following:

Table 3
Interpretation of the states and transitions in Fig. 12

States	
p1:	Faults available to introduce malfunction
p2:	Operator available
p3:	Beginning of scenario
p4:	Operator detecting or checking alarm
p5:	Operator checking the main/sub system
p6:	Operator making decision
p7:	Operator reviewing the system manual
p8:	Operator hypothesizing
p9:	System shutting down
p10:	Operator testing his/her hypothesis
p11:	Operator confirming the shutdown message
p12:	Operator confirming the hypothesis test
p13:	Operator finishing a fault diagnosis task
Immediate transitions	
t2:	Operator started to diagnose the fault
t10:	Operator confirmed the system automatic shutdown
t12:	Operator finished the fault diagnosis task
Deterministic transitions	
t1:	Operator starts diagnosing the malfunction
t7:	Operator's hypothesis formed
t8:	Operator responds after receiving the shutdown message
t9:	Operator tests after hypothesis forming
t11:	Operator confirms after testing hypothesis
Stochastic transitions	
t3:	Operator checking the alarm
t4:	Operator checking the system
t5:	Operator choosing the next step
t6:	Operator reading the system manual

1. The subjects in different clusters differed with respect to different starting time to test their hypothesis. The phenomena implies that the subjects in cluster I either generated a hypothesis faster or had more hypotheses in their mind;
2. For an aiding system, she should be introduced in the early stage of fault diagnosis so that the subject can start to test earlier (Wen and Hwang, 1994);
3. More detail behavior events can be observed with GMAT than other models (Sassen et al., 1994). The diagnostic events include the diagram of diagnosis process, the alarms, the subject checked, and the time he/she spent; and
4. TPNs have been extensively used in a discrete event system (Ajmone Marsan, 1989; Murate, 1989; Zuberek, 1991). However, results in this study demonstrate that TPNs can also be applied to model, analyze and evaluate the continuous fault diagnosis tasks.

The study has thoroughly examined the feasibility of implementing GMAT in fault diagnosis tasks. By using both DAP and TPNs to represent the human diagnostic strategy, cognitive scientists and system supervisors, as well as an operator can monitor the diagnostic behavior on-line.

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