A Symptom-Bookkeeping Aiding for Fault Diagnosis in Dynamic Systems

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ABSTRACT

In large-scale dynamic systems such as power plants, fault diagnosis becomes more difficult due to changing system states. Symptoms can be obscured by other symptoms or disappear as the operator proceeds with diagnosis or compensation. Such symptom-masking phenomena increase operator's memory load, constrain diagnostic strategies, and hence degrade performance. This study investigates the effects of a symptom-bookkeeping aid in a simulated sub-system of nuclear power plants. The results show that the aiding improved overall performance. Further analyses provide insights on the sources of cognitive difficulties and on the possible direction of supporting human diagnosis in dynamic plants.

Keywords
Fault diagnosis, symptom masking, dynamic symptoms, bookkeeping aiding

INTRODUCTION

In spite of the rapid progress of machine intelligence, the human still plays a central role in fault diagnosis in large-scale systems. With ever increasing degree of automation, fault diagnosis is also becoming more important part of human tasks in such systems. Therefore, the cognitive difficulties of fault diagnosis should weightily be considered in the design of the human-machine interface of large-scale systems.

Operator’s cognitive difficulties in diagnosis tasks obviously depend on the complexity of problem solving that is determined by the size, interactions, and dynamics of the system (Rouse & Rouse, 1979). Wohl (1982) showed that the time to diagnose increases exponentially when the amount of information required by the diagnostic task is too large to be processed by human operators.

Besides the structural complexity of a system, the dynamic characteristics of a system may also hamper the cognitive process of human problem solving for fault diagnosis. The operator must not only run a mental model of the system dynamics, but also deal with dynamically defined symptoms. The use of such symptoms is complicated by the fact that the diagnostic meaning of a symptom is not apparently indicated by the observable form of the corresponding data. That is, the abnormal behaviour of a system should be inferred on the basis of observable sensor readings that should be interpreted in the specific context of the performed operations and thus of incurred system state changes. Observed data for symptoms may take the forms of sensor readings, changes in readings, or comparisons between readings. In contrast, a symptom as is meaningful to diagnosis may be the failure in producing an expected system behaviour through a sequence of control actions starting at a certain specific system state.

In this situation, diagnostic symptoms may change their manifestation as the operator performs actions for diagnosis or compensation. Symptoms can also be obscured by other symptoms or disappear altogether. Losing a symptom and the corresponding observation due to subsequent operations may cause a severe memory problem since symptoms are contextually interpreted and not concisely described in the verbal mode. This phenomenon is referred to as symptom masking by several researchers and found to be an important cause that degrades diagnostic performance. The loss of visibility of a symptom increases operator's working memory load and constrains diagnostic strategies (Duncan and Praetorius, 1987; Yoon and Hammer, 1988; Pawlak and Vicente, 1996).

In this study, we investigated the effects of a symptom-bookkeeping aiding (SB-aiding) on fault diagnosis of a dynamic system. An experimental simulator named AFWS-D (Auxiliary FeedWater System - Diagnosis) was built and used as a target system. The results showed that the SB-aiding improved diagnostic performance in various measures. A post-hoc analysis sheds lights on the sources of cognitive difficulties of fault diagnosis in dynamic situation. A possible direction of supporting human diagnosis in dynamic plants is clearly suggested.

SYMPTOM MASKING AND BOOKKEEPING AIDING

One of the most frustrating difficulties stems from the fact that the observed data for dynamic symptoms are highly volatile. A symptom may be exhibited by different set of observations as the operator performs actions for diagnosis or compensation. It can also be overridden by other symptoms or suppressed altogether. Such symptom masking is one of the main causes that degrades diagnostic performance. The frequency of symptom masking will be even higher when the diagnostic actions and compensating actions are heavily interwoven, which is typical in emergency operations of dynamic plants (Lindgaard, 1995). When the corrective or compensating action is achieved, the system enters into a fault-masked state in which the operator has almost no opportunity for detecting abnormal system behaviour. For example, a pipe leak becomes obscured when the part is isolated by closing the valves surrounding it.

Yoon and Hammer (1988) observed that the operators experienced trouble returning the system from a fault-masked state to a state exposing abnormal behaviour. Reversing the actions that masked the fault in the backward order seldom recovers the original state. It is very hard for a operator to remember the observed data along with the context and the diagnostic connotation when the observation is no more visible or reproducible. Moreover, because a symptom is related to a set of hypotheses and the set is frequently held together in the memory by the symptom, symptom masking can induce hypothesis masking. Raaijmakers and Verduyn (1996) observed that the subjects tended to forget what they had checked and why hypotheses had been rejected. It was also found that experts performed better than novices in fault diagnosis by keeping the lookout for symptom masking and foreseeing impending problems (Duncan and Praetorius, 1987).

Computer aids for complex tasks need to be designed to supplement human cognitive limitations in attention, working memory, and information processing. Yoon and Hammer (1988) argued that information aiding has an advantage over more obtrusive automated reasoning in that it allows the human to remain in command in the task loop and inference strategy. Raaijmakers and Verduyn (1996) designed an information aid for fault diagnosis in a different domain and verified that the aid enhanced the performance considerably. However, an information aid, as passive as it is, must be designed to provide timely and usable information reflecting the human problem solving strategy (Yoon and Hammer, 1988; Konradt, 1995).

Bookkeeping aiding is the most basic information aiding that helps lessen the working memory load without producing any information the human does not have. Duncan and Praetorius (1987) as well as Pawlak and Vicente (1996) suggested that providing historical information may reduce masking problems. Konradt (1995) observed that, in a dynamic system diagnosis, resorting to the historical information was by far the most frequent strategy used by experts. To be effective, the information provided by a bookkeeping aid needs to be selected and represented to be readily used in the human diagnostic process. Especially, the historical records must facilitate the operator's recalling of the full implications of the symptoms (Rouse, 1978) and integrating them efficiently into current information without much additional work load.

In this study, we provided the chronology of the observed data along with the operations performed before and after the observations as the aiding information. The observation is a cue to the memory of more abstract symptoms regardless of their diagnostic meaning. The symptoms are also remembered more easily in association with the observable data than in abstract terms. The transforming between the aiding cue and the relevant information in memory can thus be minimised by keeping the forms of observations instead of abstract symptoms or hypotheses.

SYSTEM AND DIAGNOSIS TASK

The System

The Auxiliary FeedWater System (AFWS) in nuclear power plants was used as the environment for the diagnosis tasks in this study. The AFWS for two-loop PWR (Pressurized Water Reactor) contains redundant pipes, valves, check valves, pumps, tanks, and control devices (Figure 1) for safety. For the experiment, we built a simulated AFWS that was called ‘AFWS-D’ (Auxiliary FeedWater System-Diagnosis). In the AFWS-D, the operator opens and closes valves and turns on and off the pumps. Sensor information does not give exact numeric values, but more abstract qualitative information. For example, the qualitative information includes only the sign of the derivatives (i.e., increasing, decreasing, or stable). With these simplifications, AFWS-D still grasps considerable practicality of diagnostic situation and strategies.

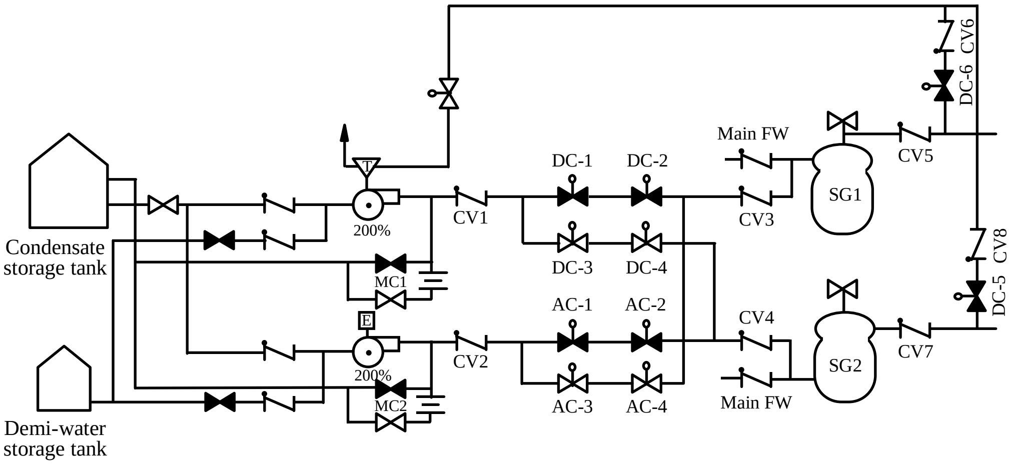

Figure 1. PWR auxiliary feedwater system

The Diagnosis Task

In AFWS-D, the operator’s task is to diagnose a fault under malfunction situation. The operator must control and observe the system continuously in order to diagnose a fault because diagnosis cannot be made by observing a single scene (system state). This requirement for diagnosis in dynamic systems at times inevitably induces the symptom masking. In AFWS-D, each component has several different behaviour modes. For example, valves have modes such as normal, fail open, fail closed, and leak. The operator’s diagnosis task in AFWS-D is to find a failed component and its behaviour mode that explain all the observed system behaviour.

AFWS-D Interface

The AFWS-D interface is shown in Figure 2. The AFWS schematic shows the states of valves and pumps in the AFWS. The operators are allowed to interact with the system through the interaction and schematic windows. Operators can perform control actions in the AFWS schematic, and the feedback of actions is provided in the interaction window. The sensor readings window, which is provided to mitigate the operator's working memory load, shows the observations made in the current scene. The help window shows all behaviour modes of each component. The SB-aiding window provides the operator with aiding information that will be discussed later.

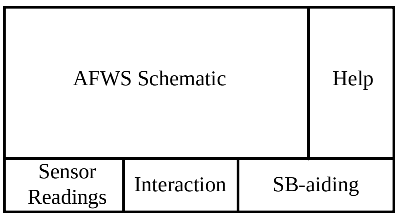

Figure 2. AFWS-D Interface

THE SYMPTOM-BOOKKEEPING AIDING

Symptom masking occurs because the system state changes as the operator takes control actions for diagnosis or compensation. Whenever a masked symptom is actively involved in the current human diagnostic reasoning, it needs to be retained in the working memory. Furthermore, when the diagnosis at a time point requires evidence from several symptoms, the currently visible symptoms and the ones in the working memory must be integrated through some common logical operations. As pointed out earlier, the content of memory contains not only the observation made but also the context of the observation as necessary to interpret it at the level of system behaviour. This means a heavy memory load as well as a severe cognitive difficulty in information processing.

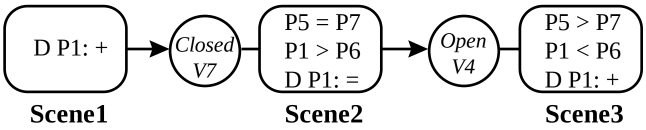

Figure 3. Dynamic Symptoms

In this system, the contextual information includes the previous state, which has been assessed by a set of previous observations, and the previous operations with their expected results in system behaviour, and finally the current observation as compared with the expectation. Since the symptom may not belong to a single static scene, it may be called dynamic or contextual. An example of such contextual symptoms are presented in Figure 3. Scene 3 has masked the symptoms in Scene 2 by opening valve V4. Instead, a new symptom may be exhibited which can only be perceived by relating Scene 3 to Scene 2 and the operation in between.

Now, the question of how such dynamic symptoms can effectively be represented by the computer should be answered. The symptoms are defined by dynamic combinations of two primitive elements: control actions and observations. Then the symptoms may be described in more abstract words that are meaningful to the current progress of diagnostic reasoning. Recording such abstract description of symptoms through overt communication will certainly be inadequate. On the other hand, the human diagostician, having once integrated the states, actions, and observations to establish a meaningful symptom, can use those elements as a cue to the memory of the abstract symptom. Even when the symptom is not immediately recalled, the operator can easily reconstruct the symptom from the elements. This consideration led us to design the SB-aiding to record the control actions and observation made by the operator and present them chronologically.

The SB-aiding provides the operator a feature by which she or he can mark scenes that are considered important and expected to be useful later. For example, the operator can mark a scene in which abnormal system behaviour is found. Using the index of the marks, the operator can review previous scenes as necessary.

THE EXPERIMENT

Twelve undergraduate students participated in the experiment. The experiment was consisted of three sessions. In Session 1 (2.5 to 3 hours), all the subjects studied training material to learn basic theories of fluid dynamics and possible fault behaviour of components of AFWS. They also learned elementary diagnostic procedures such as checking a valve leak or a pump fail-on. Then, they solved five fault problems to practice what they had learned.

In Session 2 (1 to 1.5 hours), about a week later after the basic training, the subjects returned and received a brief review of what they had learned in Session 1. Subjects were divided into two groups, the aided group and unaided group, on the basis of the diagnosis time collected in Session 1 with constraint that the sums of ordinal performance ranks for the two groups were approximately equal. The aided group were given a written instruction on how to use the SB-aiding. The instruction contained information only on the SB-aiding window, but did not include any other elements that can enhance diagnostic performance. All the subjects solved three fault diagnosis problems. The only difference between the two groups was that the SB-aiding was available to the aided group.

In Session 3 (about 1 hour), with a short break following Session 2, each subject solved five novel fault problems. Again, the SB-aiding was provided only to the aided group. These novel fault problems in Session 3 were different in nature from the ones used in Sessions 1 and 2 in that they required causal reasoning beyond simple diagnostic procedures learned or developed in Sessions 1 and 2.

THE RESULTS

Overall Effects of SB-aiding

Subjects' overall performance was measured in the amount of time to solve the novel fault problems (diagnosis time), the number of information gathering actions (IGA), and the average time to detect an abnormal system behaviour (ASB-time) after it appears.

On the average, the aided group took 48 percent less time to diagnose a fault (423.7 vs. 815.2 s, $p < 0.001$) and performed 66 percent less information gathering actions than the unaided group (11.967 vs. 34.667, $p < 0.001$). Such aiding effects appeared for all the five fault problems. The number of IGA were highly correlated with diagnosis time in both the aided group and unaided group ($r = 0.66134$, $p < 0.001$ and $r = 0.75728$, $p < 0.001$, respectively).

With regard to ASB-time, the two groups did not significantly differ although the aided group took more time than the unaided group (11.708 vs. 8.702 s, $p > 0.2$). SB-aiding certainly did not help the subjects identify the abnormal situations quickly. However, ASB-time was not correlated with total diagnosis time in the aided group ($r = 0.18505$, $p > 0.3$), while it showed a strong correlation with diagnosis time ($r = 0.58428$, $p < 0.001$) in the unaided group.

It was observed that the subjects in the unaided group tried to avoid a large deviation from an initial scene or a scene in which abnormal system behaviour happened. This strategy seemed to be employed to avoid excessive memory load as much as possible. When successive operations to observe system behaviours and to test the hypotheses overshadow a highly diagnostic scene, the subjects tended to return to the scene as soon as possible before the scene is forgotten. This interpretation is supported by the fact that the unaided group made redundant tests more frequently than the aided group. In contrast, the subjects of the aided group utilises the SB-aiding to mark and retrieve the scenes in which they observed abnormal situations or negative evidence.

Influence of SB-aiding on Symptom Masking

The above results did not explain what makes the aided group perform better than the unaided group, although SB-aiding improved overall diagnostic performance. Results from a post-hoc analysis provide such explanation. The analysis was performed on the subjects' recorded action traces and was based on a classification of the effectiveness of the subjects' actions. For example, subject's control action was classified with effective, ineffective, and masking action for evaluation.

In the post-hoc analysis, several interesting phenomena related to symptom masking were observed. In the unaided group, the subjects performed more redundant and shadowed tests that were as being ineffective. Shadowed tests refers to a test that is relevant but, being overshadowed by previous effective tests, cannot further narrow the set of competing hypotheses. Besides, after symptom masking occurred, a phenomenon called drifting was frequently observed in the unaided group. The shadowed tests during masking period (the period under symptom masking) can induce drifting. Drifting could be classified by the phases in diagnostic search strategy. During data-driven search (Yoon and Hammer, 1988), the subjects may ignore masked symptoms and pay attention to a new inefficient symptom displayed in interface. Such drifting is called symptom-drifting. Symptom-drifting hampers an effective integration of observed information and delays formation of a sound hypothesis set. Similarly, during hypothesis-driven search in which the diagnostic actions are guided by some well-specified set of hypotheses, hypothesis-drifting can occur. In this case, the subject ignores or forgets a previous hypothesis set and deals with a less efficient hypothesis set that is formed by the new symptoms. Both types of drifting were either directly related to symptom masking or excessive working memory load induced by the masking. This was verified by that the SB-aiding significantly reduced both types of drifting.

CONCLUSIONS

Symptom masking, which occurs when the operator's action changes the state of the system causing the observed symptom to disappear, increases operator's working memory load and degrades diagnostic performance. In this study, an aiding method called symptom bookkeeping aiding (SB-aiding) was proposed and evaluated for assisting the operator in fault diagnosis under symptom masking. The aiding method was intended to reduce cognitive load by providing information on the previous symptoms, which subjects should keep in working memory otherwise. The bookkeeping aid provided a chronological list of operator actions and observations that may be masked and indexed. In order to evaluate the effectiveness of SB-aiding, an experiment with a simulated Auxiliary FeedWater System (AFWS) was conducted. The experimental results showed that subjects with SB-aiding (aided group) showed better performance than subjects without SB-aiding (unaided group). A post-hoc analysis investigated the relationships between symptom masking and the effectiveness of diagnostic tests. SB-aiding also contributed to the performance by reducing the drifting cases. The experiment and the results suggest that SB-aiding can perhaps be the most basic computer support in large-scale dynamic plants.

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