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Design of Information Content and Layout for Process Control Based on Goal–Means Domain Analysis

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Abstract: With regard to the design of information content in information display, it is often claimed that the abstraction hierarchy (AH) of the work domain should be considered as a basis for identifying and structuring the information content. The primary advantage of AH-based analysis and design is that functionally abstracted information can systematically be identified and provided to the operator, which has rarely been presented in traditional displays. This study evaluated the effectiveness of providing functional information, which was abstracted and represented based on goal–means analysis along the AH, to the operator in two task situations (fault diagnosis and operation). The results showed that the operator's performance was improved with the high-level information, and the latter's utility became greater when the goal–means relations between information at different abstraction levels were exhibited. From the results, three design principles for information display can be drawn. First, information should be identified and displayed at multiple abstraction levels. Second, the goal–means relations among the abstraction levels should be explicitly presented, especially for analytical cognitive tasks. Third, information layout should support information integration along decomposition structure within an abstraction level as well as along abstraction levels.

Keywords: Abstraction hierarchy; Fault diagnosis; Functionally abstracted information; Information display design; Process control

1. INTRODUCTION

Traditional information displays in process control systems, which present physical information regarding the status of each component and subsystems of the work domains, are apt to burden human operators with great cognitive loads during performing information search, information integration, deep inference, etc. (Goodstein 1981; Vicente and Rasmussen 1990; Woods 1991). Cognitively inadequate display design has been one of the primary causes of severe safety problems in large-scale systems such as nuclear power plants (Wickens 1992). In contrast, an effectively designed display may reduce operators' cognitive loads and help them cope with complexity in dynamic systems (Woods 1991).

Advanced information technologies have increased the degree of freedom in designing information displays and helped to provide usefully processed information in various graphical formats. Naturally, there has been a great deal of research to realise more effective information display using the new technologies. However, improved display technology does not ensure a display design that allows productive and reliable user performance. It was pointed out that the key problems that the designer of an information display should systematically deal with were what information to provide and how to visualise it (Bennett et al 1997). Researchers have also pointed out that the information content and structure were crucial for effective information display and the user's performance (Vicente and Rasmussen 1992; Hansen 1995; Vicente 1995). To determine information content and structure appropriately, the designer should identify and reflect the intrinsic functional structure of the work domain. The need arises for a systematic methodology for conducting efficient work domain analysis and implementing the results in display design.

This study is concerned with the general problem of determining information content and structure that may lead to effective information displays and enhanced user performance. More specifically, to be investigated are the characteristics of the effective information and the frameworks to achieve those characteristics. The notion of ecological interface design (EID) advocated by Vicente and Rasmussen (1992) provides a practical framework to fulfil such a need. EID claims that functionally abstracted information according to abstraction hierarchy (AH) (Rasmussen 1985) supports the user tasks effectively in various domains. This paper examines the effects of providing the functional information, at different levels, that is abstracted and represented based on the goal–means analysis along the AH. The rest of this section describes the research background and clarifies the research issues in more detail.

1.1. EID and Functional Abstraction

Vicente and Rasmussen (1992) developed an ecological approach to interface design – EID – which aims to systematically represent the identified work domain constraints in the interface in order to support adaptive, goal-directed human behaviour (Flach 1990; Vicente and Rasmussen 1990). Two of the most important ingredients of the EID approach are adopting work domain analysis along the AH (Rasmussen 1985) and designing information displays to capitalise on the human's powerful pattern recognition ability (Dinadis and Vicente 1996). The AH, a multilevel knowledge representation framework for describing the goal–means structure of work domains, is used in EID to identify the information content and structure of the interface. It is this role of the AH with which this study is particularly concerned.

The validity and effectiveness of the EID framework have been widely and positively evaluated in various domains (Itoh et al 1995; Vicente et al 1995; Watanabe et al 1995; Christoffersen et al 1996; Dinadis and Vicente 1996; Pawlak and Vicente 1996; Effken et al 1997; Christoffersen et al 1998; Janzen and Vicente 1998; Lehane et al 2000; Terrier and Cellier 1999; Xu et al 1999; Burns 2000). Vicente et al (1995) compared the EID interface with a traditional interface that includes only physical information in a static diagnosis situation using DURESS (DUal REservoir System Simulation), which is a controlled process control domain. The experimental results showed that the EID interface was superior to the traditional interface, and indicated that theoretical expertise was required to make the most use of the EID interface. The advantage of the EID interface is that it appears to be closely related to the human strategies of information use. Pawlak and Vicente (1996) found that the EID interface, compared to the traditional interface, led to faster fault detection and more accurate fault diagnosis and that the difference in performance resulted from a qualitative difference in strategies.

The AH is at the centre of the EID framework for information selection and representation. Rasmussen (1986) suggested that five AH levels are useful to describe goal–means relations in process control domain. They are *functional purpose* (FP), *abstract function* (AF), *generalised function* (GF), *physical function* (PF) and *physical form* (F). These levels are used for identification and organisation of the required task information. Bisantz and Vicente (1994) demonstrated various advantages of adopting the AH as a knowledge representation framework in building DURESS. Their experiment showed that the AH provided sufficient representations to allow reasoning about novel situations, had psychological relevance and allowed the use of reasoning mechanisms independent of domain-specific information. Janzen and Vicente (1998) studied how the participants allocated their attention within the AH in the DURESS environment. The results included the finding that participants who frequently used high-level functional information showed better performance than those who mainly relied on physical information.

These results may be regarded as evidence for the utility of functionally abstracted information. Such higher-level information, when provided in addition to physical information, may support the human strategies and reduce cognitive workload involved in information processing. However, mere addition of functionally abstracted information may not necessarily result in better performance. Yoon and Hammer (1988) showed that additive information provision, when it was incompatible with human cognitive activities, could actually degrade the diagnostic performance despite the ostensible utility. Thus, it is important to select and compose functionally abstracted information so that the user is suitably supported in a given work domain and given tasks. The positive experimental results mentioned above indicate that the work domain analysis along the AH was effective in identifying and organising higher-level functional information.

However, to better appreciate the EID approach, the effectiveness of functionally abstracted information in goal–means relationships at various levels (i.e., the levels of AH) should be evaluated in diverse contexts (Moray 1997). Especially, to be analytic, the effects of functional information need to be tested independently of the effects of the sophisticated graphical representation of functional information that played a major role in most previous research studies (Lindsay 1990; Beltracchi 1991; Vicente and Rasmussen 1992). These led to the research issues that this study deals with.

1.2. Research Issues

The issues and methods of this study reflect the following research needs. First, to understand the sources of effectiveness of functionally abstracted information, and to identify the conditions for the effectiveness, experimental studies with information displays presenting different combinations of abstraction levels are required.

Second, it is also necessary to examine the effect of functional information separately from that of the usual graphical display of EID. In prior works that validated the EID framework, the benefits of the EID interface came from the combined effects of functionally abstracted information and cleverly devised geometric graphs that represent complex semantic relations (e.g., goal–means relations, causal relation, correlation, time relation) within an abstraction level or between abstraction levels. These graphical formats facilitated the operator's direct perception and enabled skill-based or rule-based perception of higher-level information. To accurately understand the roles of functional information, it is necessary to isolate the effects of abstracted functional information in the experiments.

Third, the effects of functional information may differ across tasks in the same system. Regarding the last point, several studies suggested that display effectiveness should be evaluated according to task types (Gillie and Berry 1994; Effken et al 1997; Lambert et al 1998; Terrier and Cellier 1999). Especially, Gillie and Berry (1994) argued that the display effectiveness might not generalise from passive monitoring such as static diagnosis to active operation tasks. Lambert et al (1998) stated that operation and monitoring tasks require a global vision of the process, whereas diagnosis tasks require a hierarchical vision to obtain detailed information of the process.

Table 1 compares this study with previous works on the effectiveness of the EID interface in terms of the work domain, task, inclusion of graphical formats to represent causal and quantitative relations, whether a study was done on information layout, and the level of experience of the participant in a study. In this study, the experimental investigation was focused on the effects of providing the functionally abstracted information based on goal–means domain analysis. The effects of graphical formats that were present in previous works are minimised by design as much as possible.

1.3. Previous Experiment (P-PG-PA)

The two experiments reported in this paper are preceded by a previous experiment and motivated by its results (Ham and Yoon 2001). The experiment investigated the effects of presenting functionally abstracted information of the levels of general function (GF) and abstract function (AF) for fault diagnosis task. The information at physical function (PF) level was commonly given. The experiment was conducted using a computer simulation of the secondary cooling system of nuclear power plants.

Three display types were compared in the experiment. The P display presented only PF-level information of the system. The PG display additionally presented GF-level information with the physical information. The PA display presented AF-level information, instead of the GF-level information, with the physical information.

Table 1. Previous studies on the effectiveness of EID interface

	Work domain	Task	Study on information layout	Inclusion of graphic format visualising functional information	Experience level of participants
Itoh et al (1995)	Boiling water reactor	Diagnosis	No	Yes	Experienced operators
Vicente et al (1995)	DURESS (thermal-hydraulic process simulation	Diagnosis	No	Yes	Students
Watanabe et al (1995)	Modified DURESS	Diagnosis	No	Yes	Students
Christoffersen et al (1996)	DURESS II	Fault management and operation	No	Yes	Students
Pawlak and Vicente (1996)	DURESS II	Fault management and operation	No	Yes	Students
Effken et al (1997)	Intensive care unit	Monitoring and operation	No	Yes	Students and experienced nurses
Christoffersen et al (1998)	DURESS II	Fault management and operation	No	Yes	Students
Janzen and Vicente (1998)	DURESS II	Fault management and operation	No	Yes	Students
Lehane et al (2000)	Refrigeration plant	Supervising and operation	No	Yes	Students
Terrier and Cellier (1999)	Pressurised water reactor	Powering up operation	No	Yes	Experienced operators
Xu et al (1999)	Ergonomic design based on hypertext information	Information search	No	No	Students
Burns (2000)	Process plant	Diagnosis and operation	Yes	Yes	Students
This study (2001)	Pressurised nuclear reactor	Diagnosis and operation	Yes	No	Students

The experimental results showed that both the PG and PA displays supported diagnostic tasks better than the P display did, and that the PG display was more effective than the PA display. The results implied that GF-level and AF-level information was effective in coping with the diagnostic complexity of unanticipated faults. Results supported the EID concept for its emphasis on the use of AH as a basis for analysing functional features of the system and as a basis for designing information content and structure.

However, the experiment omitted, and even raised, some research issues. In the experiment, the PG display showed a notably better performance than the PA display. A plausible explanation for this result is as follows. The diagnosis tasks in the experiment were to find the components that were not working as designed. For this, the participants had to integrate the provided PF-level information and produce information at a higher abstraction level (i.e., GF or AF) in order to assess the normality of a component. Being further abstracted than the GF-level information, the AF-level information did not have direct goal–means relations with the PF-level information. Thus, participants using the PA display had difficulty in using the AF-level information in association with the PF-level information, compared to participants using the PG display. Another, and simpler, explanation is also possible. The diagnosis may have required less use of AF-level information than GF-level information in the experiment. It is clear that information at each level of AH would have different usefulness according to the task situation. Further investigation of these issues will allow better understanding of the role of the AH in display design. In either case, it became necessary to examine the utility of AF-level information and its conditions more thoroughly.

1.4. The Experiments (PG-PGA-PGA2)

In this study, we conducted two experiments. Both examined the same three types of information display: PG, PGA and PGA2. The PG display was the same as that used in the previous experiment. The PGA display presented AF-level information in addition to the content of the PG display. The PGA2 display was the same as the PGA display in its content, but indicated goal–means relationships by its layout of information items. A possible hypothesis regarding the weak effect of AF-level information in our previous experiment is that the AF-level information may have to be used in association with GF-level information, which the PA display did not allow. Burns (2000) experimentally found that functional integration between the abstraction levels was a critical display dimension to guarantee the correct and full use of information at all abstraction levels. Comparison between PGA and PGA2 displays will reveal whether the explicit indication of goal–means relationships affects the utility of AF-level information. Further description of the displays is given later in this paper.

Both experiments are designed to evaluate the marginal effectiveness of additional AF-level information when both PF-level and GF-level information is already given. The two experiments present disparate task conditions to the operator, differing in task type and task complexity. The tasks in Experiment 1 involve diagnosis of novel faults in the system. The tasks in Experiment 2 include both operation and diagnosis, and the diagnosis tasks are more difficult than those in Experiment 1. The required operation is challenging and should be continued even when the system's behaviour becomes abnormal due to a fault.

The original motivation to have two experiments with the same types of display was to compare the effects of the same displays on tasks differing in type and complexity. However, the PGA2 display was revised in Experiment 2 after considering the results of Experiment 1. While the revision was necessary to assess the true effectiveness of AF-level information, a direct comparison between the results of Experiments 1 and 2 was made somewhat difficult.

2. WORK DOMAIN ANALYSIS AND THE DISPLAY TYPES

2.1. The Secondary Cooling System of Nuclear Power Plants

Typical characteristics of complex human–machine systems (Vicente 1999) include large problem spaces, dynamic system states, complex coupling between subsystems, uncertainty in the data and the need for disturbance control. We chose the secondary cooling system of pressurised water reactor nuclear power plants (PWR-NPP), which possess such characteristics, as the experimental system. Figure 1 shows the computer simulation of the system used in the experiment. Although simplified, it includes all the essential elements of the functions and dynamics of a real secondary cooling system.

The primary cooling system in NPP generates thermal energy by the operation of the nuclear reactor, and the secondary cooling system produces electricity by the operation of the turbine using thermal energy transferred from the primary cooling system. The secondary cooling system also circulates the feedwater continuously to keep the pressure of the primary system within a safe range. The objectives of the secondary cooling system are to maximise the productivity of electricity generation and to manage the water flow for the safety of the NPP. An important characteristic of the secondary cooling system is that water exists in a two-phase mixture of steam and liquid. This increases the complexity of controlling the system.

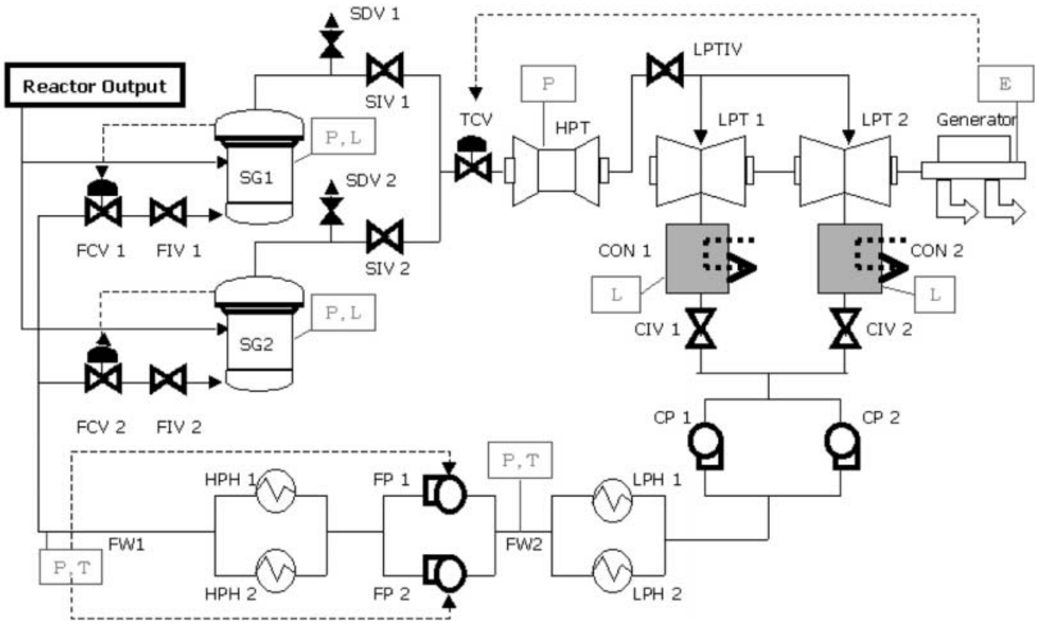

Fig. 1. The work domain: the secondary cooling system of NPP.

The secondary cooling system consists of four subsystems: the steam generation system (SGS), the turbine operation system (TOS), the condensation system (COS) and the feedwater supply system (FSS). The SGS boils the feedwater provided from the FSS and generates steam to transfer to the TOS. The components of the SGS include the steam generators (SG1, SG2), steam dump valves (SDV1, SDV2) and steam isolation valves (SIV1, SIV2). The TOS runs turbines to produce electrical energy using steam pressure, that is, it transforms the thermal energy into electrical energy. The components of the TOS are the turbine control valve (TCV), the high-pressure turbine (HPT), the low-pressure turbines (LPT1, LPT2), the low-pressure turbine isolation valve (LPTIV) and the generator (GEN). The COS condenses steam into water (feedwater) to feed it to the steam generator. The components of the COS are the condensers (CON1, CON2), the condenser isolation valves (CIV1, CIV2) and the condensation pumps (CP1, CP2). The FSS is concerned with transferring feedwater to the SGS. The components of the FSS are the low-pressure heaters (LPH1, LPH2), the high-pressure heaters (HPH1, HPH2), the feedwater pumps (FP1, FP2), the feedwater control valves (FCV1, FCV2), and the feedwater isolation valves (FIV1, FIV2).

Three types of valves are used for controlling the flow of water or steam. The first is the isolation valve, which is usually open under normal situations. However, the isolation valve should be closed to block the flow of water (or steam) when a monitoring variable related to the water (steam) flow shows an extremely high value. The second is the dump valve, which usually remains closed under normal situations. The operator should open the dump valve in order to release the steam in a steam generator when the pressure of the steam generator approaches the high hazard region. The last is the control valve, with which the operator can manipulate the flow of water (steam) quantitatively, unlike the isolation and dump valves, which have only two states (open and close). The state of a control valve is dependent on the operator's control action.

2.2. Knowledge Analysis of the Work Domain

It is necessary to analyse the work domain in order to identify and organise the knowledge requirements for effective control of the system. The analysis first begins with identifying monitoring and control variables (Vicente and Rasmussen 1992; Dinadis and Vicente 1999). Monitoring variables are those that should be observed to acknowledge the system's states. Control variables are those that can be manipulated to influence the system's state. Secondly, the underlying dynamics of the work domain are described. Finally, the work domain is analysed in terms of the abstraction hierarchy in order to describe the purpose of work domain, the functions of the work domain and their mutual relationships, and the way in which the functions are implemented. From the result of this analysis, the knowledge to be represented in an ecological display is identified.

2.2.1. Process Variables for Monitoring and Control

Table 2 provides a complete list of process variables and their labels. The work domain has 11 monitoring variables, which the operator should continuously observe in order to

Table 2. Complete list of process variables and their labels

Monitoring variables related to system state
(Level variables; L_ means level of)
L_SG1, L_SG2, L_CON1, L_CON2
(Pressure variables; P_ means pressure of)
P_SG1, P_SG2, P_HPT, P_FW1, P_FW2
(Temperature variables; T_ means temperature of)
T_FW1, T_FW2
(Others)
D_EP: demand of electricity
Control variables
(Variables with binary states)
SDV1, SDV2, SIV1, SIV2, FIV1, FIV2, LPTIV, CIV1, CIV2
CP1, CP2, HPH1, HPH2, LPH1, LPH2
(Variables with quantitative states)
FCV1, FCV2, TCV, FP1, FP2
Other observed variables
(Flow rate variables; F_ means flow rate of)
F_SDV1, F_SDV2, F_SIV1, F_SIV2, F_FIV1, F_FIV2
F_FCV1, F_FCV2, F_TCV, F_LPTIV, F_CIV1, F_CIV2
F_CP1, F_CP2, F_FP1, F_FP2
(Heat rate variables; H_ means heat rate of)
H_HPH1, H_HPH2, H_LPH1, H_LPH2
(Others)
T_RO: temperature of reactor output
F_RO_SG1: flow rate from reactor output to SG1
F_RO_SG2: flow rate from reactor output to SG2

Table 3. Constraints governing the work domain under normal operation

Normal ranges (values) of process variables	
Flow rate of all valves : 1 ~ 5	
D_EP = 20 ~ 100 (60)	T_RO = 180
L_SG1 = 30 ~ 70 (50)	L_SG2 = 30 ~ 70 (50)
P_SG1 = 100 ~ 140 (120)	P_SG2 = 100 ~ 140 (120)
P_HPT = 100 ~ 140 (120)	(P_HPT(0) = ((D_EP - 20) / 2) + 100; initialisation)
L_CON1 = 80 ~ 120 (100)	L_CON2 = 80 ~ 120 (100)
P_CON1 = 10 (constant)	P_CON2 = 10 (constant)
P_FW1 = 0 ~ 10	P_FW2 = 0 ~ 10
H_LPH1 = 3	H_LPH2 = 3
H_HPH1 = 2	H_HPH2 = 2
Algebraic equations	
F_FCV1(t) = F_FIV1(t)	F_FCV2(t) = F_FIV2(t)
F_SDV1(t) = 1 (if SDV1 is open)	F_SDV2(t) = 1 (if SDV2 is open)
F_TCV(0) = D_EP/20	F_LPTIV = D_EP/20
F_TCV(t) = F_SIV1(t) + F_SIV2(t)	
F_CIV1(t) + F_CIV2(t) = F_CP1(t) + F_CP2(t) = F_FP1(t) + F_FP2(t)	
State equations	
L_CON1(t) = L_CON1(t-1) + (F_LPTIV(t) / 2) − F_CIV1(t)	
L_CON2(t) = L_CON2(t-1) + (F_LPTIV(t) / 2) − F_CIV2(t)	
L_SG1(t) = L_SG1(t − 1) + F_FIV1(t) + F_RO_SG1(t) − F_SDV1(t) − F_SIV1(t)	
L_SG2(t) = L_SG2(t − 1) + F_FIV2(t) + F_RO_SG2(t) − F_SDV2(t) − F_SIV2(t)	
P_SG1(t) = P_SG1(t − 1) + F_FIV1(t) − F_SIV1(t) − F_SDV1(t) + ((((T_RO(t) + T_FW1(t)) / 2) − 120) * F_FIV1(t)) /(L_SG1(t)) + (P_SG1(t − 1)) / (L_SG1(t) + F_FIV1(t) − F_SIV1(t) − F_SDV1(t)) − (P_SG1(t − 1) / L_SG1(t − 1))	
P_SG2(t) = P_SG2(t − 1) + F_FIV2(t) − F_SIV2(t) − F_SDV2(t) + ((((T_RO(t) + T_FW1(t)) / 2) − 120) * F_FIV2(t)) /(L_SG2(t)) + (P_SG2(t − 1)) / (L_SG2(t) + F_FIV2(t) − F_SIV2(t) − F_SDV2(t)) − (P_SG2(t − 1) / L_SG2(t − 1))	
P_HPT(t) = P_HPT(t − 1) + F_TCV(t) − F_LPTIV(t − 1)	
P_FW1(t) = P_FW1(t − 1) + (F_FP1(t) + F_FP2(t)) − (F_FCV1(t) + F_FCV2(t))	
P_FW2(t) = P_FW2(t − 1) + (F_CP1(t) + F_CP2(t)) − (F_FP1(t) + F_FP2(t))	
T_FW1(t) = ((((F_FP1(t) + F_FP2(t)) / 2) * (T_FW2(t) * (H_HPH1(t) + H_HPH2(t)))) + (P_FW1(t − 1) *T_FW1(t − 1))) / (P_FW1(t − 1) + F_FP1(t) + F_FP2(t))	
T_FW2(t) = ((((F_CP1(t) + F_CP2(t)) / 2) * ((P_CON1 + P_CON2) / 2) * (H_LPH1(t) + H_LPH2(t))) +(P_FW2(t − 1) * T_FW2(t − 1))) / (P_FW2(t − 1) + F_CP1(t) + F_CP2(t))	
Others	
Temperature of seawater through condenser is constant (unlimited heat sink)	
Isolation valve is open under normal state.	
Dump valve is closed under normal state	
D_EP ∝ P_HPT	

evaluate the system's state. Each monitoring variable should be controlled within a range between its maximum and minimum levels to meet the safety demands. When a fault occurs in a component, some of the monitoring variables can rapidly approach the maximum or minimum level, and the system can run into an emergency situation. In such a case, to control the variables effectively, the operator should properly understand the dynamic principles of the work domain. Therefore, it is important for the interface to represent the work domain knowledge in order to support the operator's mental model.

The work domain also has control variables, which can be manipulated by the operator to change the system's state. By working on the control variables, the operator can also collect the process information that is required for fault diagnosis. In this respect, a good interface should also be capable of indicating what the relevant control variables are and when and how they should be manipulated.

2.2.2. The Dynamics of the Work Domain

The behaviour of the work domain is based on the principles of thermodynamics and hydrodynamics. Table 3 shows the basic dynamic constraints governing the work domain under normal operation. The normal ranges of process variables are defined by the values of their maximum and minimum levels. The algebraic equations are the relationships that hold over the flows of water or steam. State equations define how the monitoring variables behave in relation to other process variables. Although Table 3 represents somewhat simplified dynamics of the real secondary cooling system of an NPP, the simulated system based on it still carries representative characteristics of the complex engineering systems.

2.2.3. Goal–Means Analysis of the Work Domain

Work domain analysis based on the AH provides the ground for designing an ecological interface. The analysis identifies the goal–means relations between functions at different abstraction levels of a work domain in a systematic way. As previously mentioned, five AH levels are useful for

Level	Properties
Functional purpose	Generate electricity as demanded
	Keep safety
Abstract function	Conservation of mass (feedwater and steam)
	Conservation of energy
Generalised function	Heat transfer (heating, cooling)
	Mass flow
	Feedback control
	Power supply
Physical function	Steam generation
	Condensation
	Feedwater heating
	Feedwater/steam stream
	Flow control
	Turbine operation
Physical form	Spatial layout
	Appearance

Fig. 2. An AH representation of the work domain.

describing goal–means relations in the process control domain. The analysis begins with identifying the properties at each level of the AH in the work domain. Figure 2 shows the properties at each level of the AH in the work domain and Fig. 3 depicts how the properties are related to each other within each level of the AH. The following is a description of the work domain according to the five AH levels.

- *Functional purpose (FP)*. The purposes of the work domain are (1) to produce electricity as demanded and (2) to maintain safety.
- *Abstract function (AF)*. The causal relations in the work domain are first described according to the first principles at this level. In this domain, the relations are represented in terms of the conservation of mass and energy for the steam generator and condenser. The FP justifies the reason why the conservation laws of mass and energy should be kept. The functions at the AF level work as the basis for accomplishing the FP and they are in turn realised by means represented at the levels below.
- *Generalised function (GF)*. This level represents the work domain in terms of standard engineering functions. The GFs of the work domain include heat transfer (heating and cooling), mass flow, feedback control and power supply.
- *Physical function (PF)*. The GFs are represented by physical mechanisms at this level. The PFs in our case are the variables that the operator has control over, which include steam generation, condensation, feedwater heating, feedwater/steam stream, flow control and turbine operation.
- *Physical form (F)*. This function level describes the appearance, condition and location of each component, and spatial proximity among the components.

After identifying the properties within each level of the AH, we need to represent the relationships among the properties across levels. Figure 4 illustrates how the proper-

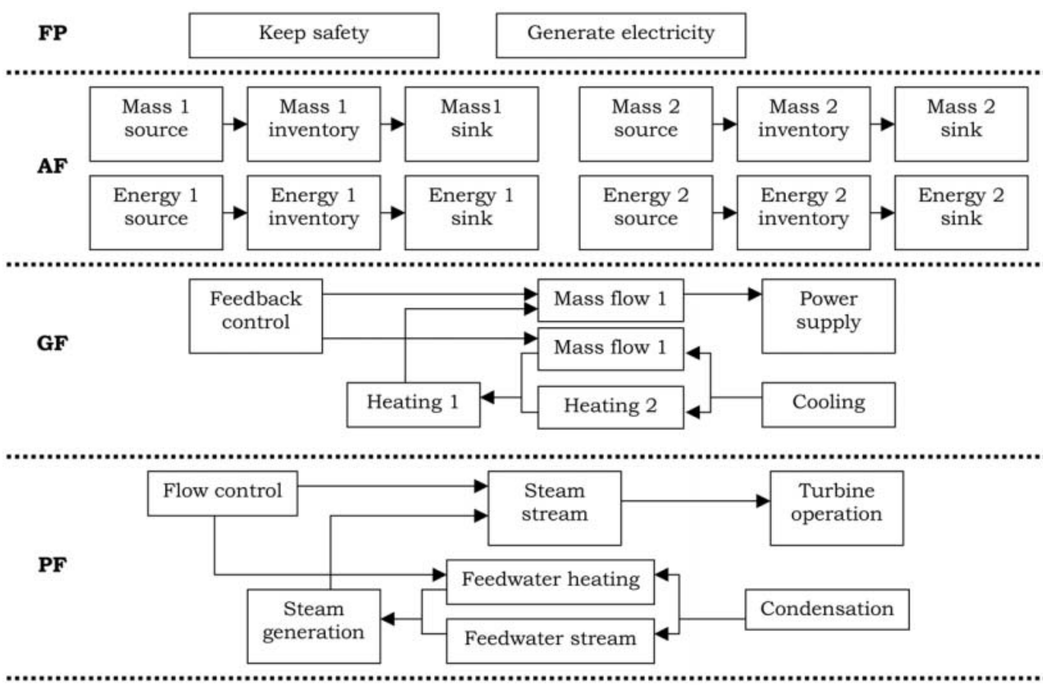

Fig. 3. Relationships within levels of AH of the work domain.

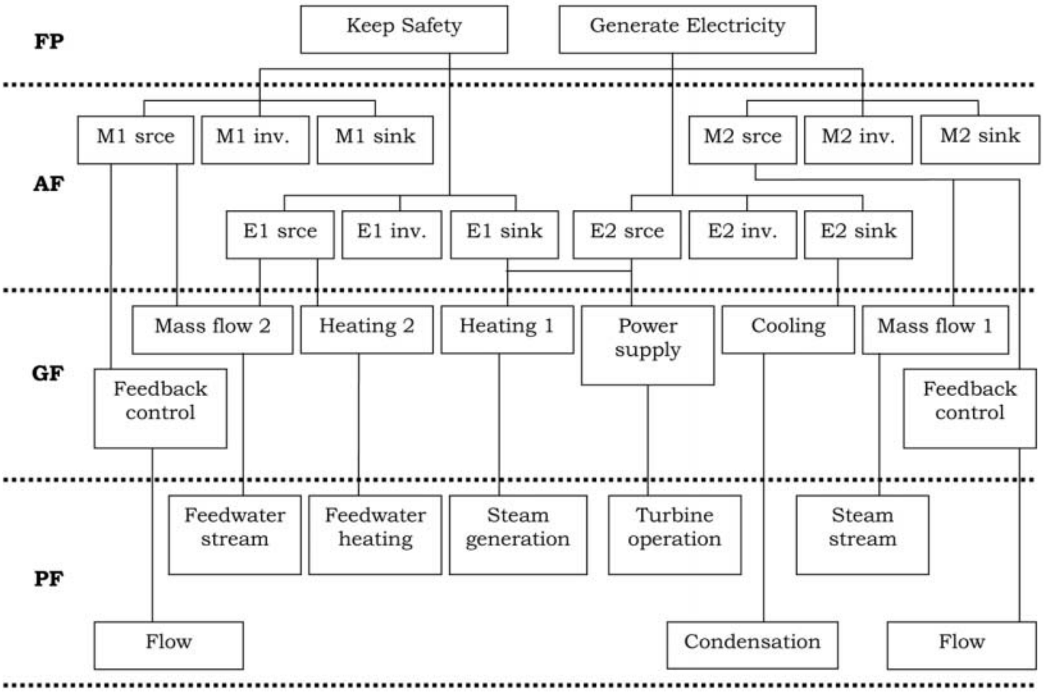

Fig. 4. Mapping between levels of AH of the work domain.

ties at different levels are related in terms of goal–means relations. An important structural feature shown in the figure is the many-to-many relations among functions of adjacent levels. That is, a goal in the upper level can be achieved by several means in the lower level and, conversely, a means can be used for several goals. For example, Mass flow 2 in the generalised functions has relations to both Mass 1 source and Energy 1 source. Referring to Fig. 1, Mass 1 inventory is composed of the two steam generators (SGs). Their levels and pressures then determine Mass 1 balance and Energy 1 balance, respectively. When the operator changes the input flow rate to the two SGs (i.e., Mass 1 inventory), he/she should consider how the change would influence their pressures and levels (i.e., Energy 1 balance and Mass 1 balance).

The information content and structure summarised in Figs 2–4 should be represented on the interface to follow the EID concept, which implies that an interface lacking appropriate levels of AH should lead to an ineffective human performance.

2.3. The Display Types

To investigate the effectiveness of the functionally abstracted information as stated in the Introduction, we designed three display types to use in two experiments.

Since the purpose of the experiments was to compare operator performance, the displays were plainly designed to ensure fair comparison rather than to improve performance. Ingenious interface features were inhibited since they might produce peculiar interaction with particular display types or tasks. The controls were grouped in a separate panel and remained the same for all the display types, because mingling the information items and the control objects might hinder the investigation of the hypothesised informational effects. However, the displays were designed not to impose unnecessary memory load. The parts were located in relative positions to assimilate the topographic layout of the schematic with which the participants were trained. The displays were tested and refined to look more natural to the users.

Figure 5 shows a PG display representing three functional levels of the AH: FP (functional purpose), GF (generalised function) and PF (physical function). Both FP-level and PF-level information can be found in traditional displays, whereas GF-level information has rarely been included in them. The GF-level information helps to determine whether the PF-level functions work well as operated. The examples on the PG display are the flow rates at valves and the heat transferring rates at heaters. If the GF-level information on he PG display is useful, the operator can save the effort of processing PF-level information to infer GF-level qualities.

In the PG display, the ranges between maximum and minimum levels, which are coloured red, set the goals to be accomplished by the operator's control (i.e., safety goal). The electric demand indicator sets the goal of the amount of electricity to be produced per unit time (i.e., productivity

Fig. 5. PG display.

goal). Physical functions are represented as the states of the monitoring variables and control variables. The states of the monitoring variables are represented by the heights of the bars, which should normally stay within the designated ranges. Different types of variables are distinguished by colours: level variables are yellow, pressure variables blue and temperature variables green. The control variables with binary states are presented in *Control Panel 1* and the control variables with continuous states are included in *Control Panel 2*. This arrangement remains the same with all the types of display.

The operator can change the states of those binary variables in *Control Panel 1* by a mouse click on the corresponding buttons. When a binary variable is open or on, its button appears red; when closed or off, green. Similarly, the operator can change the states of the variables in *Control Panel 2* by clicking the mouse at the desired points. The far right panel including *Training Problems*, *Main Problems* and *Information panels* is for experimental use and is also common to all types of display.

The basic design represented in the PG display is retained in all the displays used in the two experiments. The control panels and the experimental information part remain the same. In the monitoring panel, the elementary bar graph shapes are preserved and, according to the information content, only the layout of the information is changed. The shapes of those common elements as well as the additional information elements at AF level are made as simple as possible. The displays are different from the usual EID displays in that no diagrammatic or graphical representation was used to present the dynamic relations among variables.

The AF-level information in Figs 3 and 4, which embraces the notions of mass and energy, is missing in the PG display. In contrast, PGA and PGA2 displays carry AF-level information in terms of the balances between inflows and outflows. Figure 6 depicts the PGA display. For example, the mass balance of SG1 shows how the input flow rate to SG1 and the output flow rate from it are balanced. If the balance is maintained, it is indicated by the sign '='. The sign '>' indicates that the input flow rate is greater than the output flow rate. The sign '<', denotes the opposite state. The balances of other variables are indicated in the same manner. The control variables are manipulated in the same way as in the PG display.

Finally, as shown in Fig. 7, the PGA2 display provides the same information as the PGA display. However, in the PGA2 display the information is grouped together according to goal–means relations. For instance, mass and energy balances of SG1 are grouped with the GF-level functions (F_FIV1, F_FCV1, F_SDV1 and F_SIV1), which are used to achieve those balances. The control variables are manipulated in the same way as the other displays.

Fig. 6. PGA display.

Fig. 7. PGA2 display.

3. EXPERIMENT 1

3.1. Purposes

As described in Sections 1.2 and 1.4, this experiment was devised to investigate two main questions. The first is whether the value of AF-level information would be additionally effective when it is provided with GF-level information in the task of fault diagnosis. The second is whether the utility of functionally abstracted information for the fault diagnosis task becomes greater when it is organised according to goal–means relations.

3.2. Method

3.2.1. Participants

Twelve undergraduate students at KAIST volunteered and participated. Of those, nine were male and three were female. None of them had have any previous experience in process control or thermodynamics.

3.2.2. Experimental Design and Procedure

Twelve participants were randomly assigned to one of the three groups for three display types: PG, PGA and PGA2. Each display group had three males and one female, and experienced only one of the three display types during the training and the main test. The experiment used a split-plot design, so that the participants were nested within the display types, whereas display types and problems were crossed (Kirk, 1968). This type of design is also called ‘nested factorial design’ (Montgomery, 1991).

The experiment was conducted as follows. The participants first read the training material, which provided the required knowledge for operation of the system. Then the experimenter tested with written questions whether the participants had learned the training material correctly. The participants were then further trained by discussing the points they had not understood with the experimenter.

In the next session, the participants read the manual relating to the display assigned to them and practised using the assigned display. The experimenter assessed and approved their principle knowledge on the work domain and tasks before they were allowed to proceed to exercise with the training problems. Six exercise diagnostic problems were provided. The training sessions altogether took approximately 3 hours. The system was relatively simple, so that most participants showed stabilised performance in the middle of the training session. To ensure the validity of the experiment further, however, only the participants who showed stable task performance and the sign of mature principle knowledge were allowed to enter the main test session. The training problems were selected to be commensurate in complexity with the main problems.

In the main test session, the participants solved nine fault diagnosis problems that were common to all three groups.

3.2.3. Experimental Task and Problems

The problem-solving tasks in the experiment were to diagnose unfamiliar faults. Fault diagnosis being a difficult and critical problem-solving task, novel fault diagnosis is known to be more challenging. For novel faults, where routine diagnostic rules do not apply, the operator should solve the problems in a knowledge-based manner. The information content and structure represented in the interface bear more importance in such cases.

Table 4 describes the types of faults that appeared in the experiment. The fault diagnosis task in the experiment can

Table 4. Types of faults in the experiment

Component	Fault	Description
Isolation/dump valve	Fail closed	Whatever you command, valve remains fully closed
	Fail open	Whatever you command, valve remains fully open
Control valve	Too high	Flow rate of valve is more than what you command
	Too low	Flow rate of valve is less than what you command
Condensation pump	Fail on	Whatever you command, pump remains fully on
	Fail off	Whatever you command, pump remains fully off
Feedwater pump	Too high	Flow rate of pump is more than what you command
	Too low	Flow rate of pump is less than what you command
Reactor output	Increase	Temperature of reactor coolant is higher than normal temperature, so that pressure of SG1 and SG2 increase
	Decrease	Temperature of reactor coolant is lower than normal temperature, so that pressure of SG1 and SG2 decrease
SG1	Tube rupture	SG1 tube through which reactor coolant flows ruptures and coolant flows into SG1, so that level of SG1 increases
SG2	Tube rupture	SG2 tube through which reactor coolant flows ruptures and coolant flows into SG2, so that level of SG2 increases
Heater	Too high	Heat rate of heater is higher than normal rate
	Too low	Heat rate of heater is lower than normal rate

Table 5. Problems in Experiment 1

Problem	Training	Main
1	FCV1 too high	FIV1 fail closed
2	SIV1 fail closed	SDV2 fail open
3	FCV2 too low	FP2 too high
4	LPH1 too high	LPTIV fail closed
5	FIV2 fail closed	TCV too low
6	SG1 tube rupture	SG2 tube rupture
7	SIV2 fail open	HPH2 too low
8		Reactor output increase
9		CIV1 fail open

operationally be defined as to find a faulty component and to determine the type of fault with a legitimate ground. That is, the participant should be able to explain how the diagnosed fault caused the observed abnormal situation. To perform the task, the operator should gather process information by manipulating control variables, integrate the information to establish hypotheses and test the formed hypotheses.

Table 5 shows the problems used in the experiment. Although all of the problems were unfamiliar to the participants, the complexity of the problems varied. The complexity was related to the number of initial symptoms and the required number of activities for information collection and integration for correct diagnosis.

3.2.4. Performance Measures

Six performance measures were used for evaluating diagnostic performance. They were the *diagnosis time*, the *number of trials* to correctly find the cause, the *number of control actions*, the *number of warning alarms* given to the participant as the monitoring variables approached their limits, the *number of exceed alarms* that arose when the monitoring variables exceeded the limits and the *number of automatic recoveries* that were triggered to help the participant recover the system from extremely unsafe states.

To collect data for the measures, the simulation system logged all the participants' control actions, the state of all the system variables, the interval time between control actions, and the alarms. The participants' actions and the displays were also recorded using a video camera so that the logged records could be correctly interpreted. Verbal protocols were not collected since the mental workload for verbalising may interfere with the participants' problem solving.

3.2.5. Apparatus

The simulation system was written in VISUAL BASIC 6.0 and was run on a Pentium II computer with a 17-inch monitor.

3.3. Results and Discussion

Table 6 shows the average and standard deviation of the performance measures. The PGA2 display showed the best performance and the least standard deviation in all the measures, with the PGA display following next. ANOVA results, as summarised in Table 7, showed that the displays failed to exhibit statistically significant effects except in the number of warning alarms. A multiple comparison of display types using Duncan's test also found a significant difference between display types only in the measure. Diagnosis time and the number of exceed alarms, however, showed a great difference in the mean value and deviation among the displays. It was hinted that the statistical test had not enough power due to the large personal variation and relatively small sample size. Overall, it is reasonable to conclude that, while the effect of AF-level information was not sufficiently strong, the participants using the information tended to show more stable operational performance.

Table 6. Average (standard deviation) of performance measures in Experiment 1

	PG		PGA		PGA2
Diagnosis time (seconds)	220.00 (231.50)	–	139.81 (225.86)	– –	125.89 (118.25)
No. of trials	1.17 (0.38)	–	1.06 (0.23)	– –	1.14 (0.49)
No. of control actions	9.08 (12.99)	–	7.14 (7.33)	– –	8.08 (8.33)
No. of warning alarms*	38.78 (59.00)	*	15.36 (43.44)	* –	8.97 (17.65)
No. of exceed alarms	29.06 (51.17)	–	16.50 (46.85)	– –	7.08 (13.42)
No. of automatic recoveries	0.22 (0.76)	–	0.06 (0.23)	– –	0.06 (0.23)

Asterisks (*) following the names of performance measures indicate whether the measure is statistically significant at 5% in display group factor.
Column on the left of PGA column shows the results of pairwise comparison between PG and PGA (*significant at 5%).
Column on the left of PGA2 column shows the results of pairwise comparison between PGA2 and PG (top row), and PGA2 and PGA (bottom row) (*significant at 5%).

Table 7. P_values summarised from ANOVA in Experiment 1

	Diagnosis time	No. of trials	No. of control actions	No. of warning alarms	No. of exceed alarms	No. of automatic recoveries
Group	0.3125	0.3520	0.8473	0.0371*	0.1179	0.5239
Problem	0.0013**	0.0705	0.0001**	0.4667	0.6857	0.4870
Group* Problem	0.3013	0.0988	0.6442	0.2284	0.2622	0.7607

ANOVA table example (diagnosis time measure)

	d.f.	SS	MS	F	P_value
Group	2	1.0277	0.5139	1.33	0.3125
Subject (G)	9	3.4842	0.3871		
Problem	8	2.8084	0.3510	3.64	0.0013**
Group* Problem	16	1.8294	1.1143	1.18	0.3013
Problem* Subject (G)	72	6.9511	0.0965		

*Significant at 5%; **significant at 1%.

The weak marginal effect of AF-level information was hardly a surprise. As mentioned in the Introduction, our previous study had revealed the ineffectiveness of AF-level information when lacking GF-level information. Therefore, supplementing the AF-level information to the PG display, which had already proved to be strongly effective for itself, would not easily show an additional improvement. However, considering the characteristics of AF-level information in process control, one can imagine that AF-level information would be of more help in monitoring and controlling the system. This point is investigated in Experiment 2, in which problems are more complex and include operational tasks. It is also noted that AF-level information, to be effective, may have to be used in close association with the related GF-level information. This motivated the design of the PGA2-R display for use in Experiment 2.

The last point to note is that the AF-level information was given in a separate and alphanumerical format for experimental use. It is possible that the integrated graphical format as used in EID could have been much more effective in the given problems. Thus, the weak effects of the AF-level information in this experiment should not be generalised to the ordinary EID displays.

4. EXPERIMENT 2

4.1. Purposes and Displays

Experiment 2 differs from Experiment 1 in that it tested more demanding task situations to further examine the utility of AF-level information. First, the faults were more complex to diagnose. Second, the problems included challenging operation tasks. The motivation was based on the assumption that the relative effectiveness of the information levels may be affected by the types and complexity of the problems to solve.

In this experiment the three display types are evaluated: PG, PGA and PGA2-R. The PGA2-R display is a revised version of the PGA2 display. Compared to the PGA2 display, it presented the goal–means relations among the displayed items more explicitly (Fig. 8). For example, F_FCV1 and F_FIV1 (Mass 1 and Energy 1 input), F_SDV1 and F_SIV1 (Mass 1 and Energy 1 output), L_SG1 (Mass 1 inventory) and P_SG1 (Energy 1 inventory) are grouped under mass and energy balance information. The revision is motivated by the results of Experiment 1. A possible hypothesis regarding the weak effect of AF-level information in Experiment 1 is that the AF-level information may have to be used in close association with the GF-level information and the PGA display did not sufficiently support the association. The revision aims at a more practical evaluation of the effectiveness of the AF-level information. However, this would also make direct comparison between the results of Experiments 1 and 2 somewhat difficult.

4.2. Method

4.2.1. Participants

Fifteen graduate students at KAIST participated in the experiment. Of those, twelve were male and three were female. None of the participants had previous experience in process control or thermodynamics.

4.2.2. Experimental Design and Procedure

The experiment had the same experimental design and procedure as Experiment 1. Each display group had four

Fig. 8. PGA2-R display.

males and one female. The training sessions took around 4 hours.

4.2.3. Experimental Task and Problems

The tasks in this experiment were to conduct complicated process control including operation and fault diagnosis. First, from the beginning of the experiment, the participants should set the values of several monitoring variables within the specified range in a given length of time (480 seconds). An example of the operation tasks was 'Set the level of SG1 within the range of 90 ~ 105; set the pressure of SG2 within the range of 110 ~ 115'. Each problem had at least three simultaneous operation goals of this type. The participants had to reach the operation goal states and maintain the system within the states. Because the operation goals are interrelated to each other, the participants should have appropriate mental models concerning the overall structure and functions of the work domain to achieve the goals in an efficient way.

During the operation, faults occurred at specific times. When a fault occurred, the participants had to diagnose the fault and continue the operation task taking the effects of the fault into consideration (fault compensation) until the end of the problem. Each problem differed in the time of fault occurrence, so that the participants could not predict the occurrence. During the existence of a fault, the complexity of problem solving became greater because the fault diagnosis and fault compensation tasks, which were demanding in themselves due to varied dynamics, had to be performed at the same time. The information content and structure in the display could be more severely tested for effectiveness in such a task situation. Table 8 shows the problems used in this experiment. Some diagnosis problems were different from those in Experiment 1. This change was necessary to manage the complexity of tasks consisting of operation and diagnosis.

4.2.4. Performance Measures

Eleven measures were used to evaluate problem-solving performance in this experiment. Of those measures, five were previously used in Experiment 1: the *diagnosis time*, the *number of control actions*, the *number of warning alarms*, the *number of exceed alarms* and the *number of automatic recoveries*. The other six new measures were as follows:

- *goal_reach time*: the elapsed time until the operation goals were achieved;
- *SSD (sum of state deviation) total*: how much the system states deviated from the specified operation goal states throughout the problem;
- *SSD before goal_reach*: SSD before operation goals are achieved;

Table 8. Problems in Experiment 2

Problem	Task goals	Fault	Fault occurrence time (seconds)
Training-1	45 <= L_SG1 <= 55 120 <= P_HPT <= 130	FCV1 too high	120
Training-2	45 <= L_SG2 <= 55 110 <= P_HPT <= 120	SIV1 fail closed	180
Training-3	50 <= L_SG1 <= 60 100 <= P_SG2 <= 115 80 <= L_CON1 <= 90	FCV2 too low	120
Training-4	100 <= P_HPT <= 110 55 <= L_SG2 <= 65 40 <= L_SG1 <= 50	LPH1 too high	150
Training-5	55 <= L_SG1 <=65 110 <= L_CON1 <= 120 0 <= P_FW1 <= 5	FIV2 fail closed	180
Training-6	100 <= P_SG1 <= 110 90 <= L_CON2 <= 100	SIV2 fail closed	150
Main-1	90 <= P_SG2 <= 115 115 <= P_HPT <= 125 100 <= L_CON1 <= 110	FIV1 fail closed	180
Main-2	50 <= L_SG2 <= 60 120 <= P_HPT <= 130 90 <= L_CON2 <= 100	SDV2 fail open	240
Main-3	50 <= L_SG1 <= 60 100 <= P_SG2 <= 130 90 <= L_CON2 <= 100	FCV2 too high	240
Main-4	50 <= L_SG1 <= 60 50 <= L_SG2 <= 60 120 <= P_HPT <= 135 2 <= P_FW1 <= 7	LPTIV fail closed	300
Main-5	45 <= L_SG1 <= 55 110 <= P_HPT <= 125 90 <= L_CON2 <= 100 2 <= P_FW1 <= 7	TCV too low	200
Main-6	55 <= L_SG1 <= 65 90 <= P_SG2 <= 110 125 <= P_HPT <= 135	FCV1 too low	240
Main-7	110 <= P_SG1 <= 130 45 <= L_SG2 <= 55 100 <= L_CON2 <= 115	HPH1 too high	240
Main-8	55 <= L_SG2 <= 65 90 <= L_CON1 <= 100 115 <= P_HPT <= 125 3 <= P_FW1 <= 8	TCV too high	200

- *SSD after goal_reach*: SSD after operation goals are achieved until the end of the problem;
- *SSD before fault occurrence*: SSD before the fault occurrence;
- *SSD after fault occurrence*: SSD after the fault occurrence until the end time of problem.

4.2.5. Apparatus

This experiment used the same apparatus as Experiment 1.

4.3. Results and Discussion

Table 9 shows the average and standard deviation of the performance measures. The PGA2-R display showed the best average performance and the least standard deviation in all the measures. The PGA display produced better average performance and smaller standard deviation than the PG display.

Table 9 also shows the results of multiple comparisons of three display types based on Duncan's test. The test showed that the PGA2-R display was better than the PG display in all measures except the number of control actions and SSD before fault occurrence. The PGA2-R display outperformed the PGA display in three measures: goal_reach time, fault_diagnosis time and SSD after fault occurrence. The PGA display was superior to the PG display in three measures: SSD after fault occurrence, the number of exceed alarms and the number of activations of automatic recovery.

Figure 9 shows the average performance of the three groups in two measures: SSD before fault occurrence and

Table 9. Average (standard deviation) of performance measures in Experiment 2

	PG		PGA		PGA2-R
Goal_reach time(ranked order) *	9.06 (4.61)	–	8.56 (4.45)	* *	6.38 (3.24)
Diagnosis time(ranked order)**	10.63 (3.15)	–	8.78 (4.10)	** **	4.60 (3.17)
SSD (sum of state deviation) total**	718.22 (399.76)	–	520.25 (324.80)	** –	329.42 (245.28)
SSD before goal_reach(ranked order)	9.03 (4.80)	–	8.49 (4.34)	* –	6.49 (3.45)
SSD after goal_reach**	238.92 (221.97)	–	103.99 (142.53)	** –	23.71 (55.20)
SSD before fault occurrence	323.73 (214.74)	–	310.22 (218.63)	– –	270.59 (206.22)
SSD after fault occurrence**	394.49 (294.29)	**	210.03 (188.95)	** **	58.83 (104.17)
No. of control actions	37.70 (11.51)	–	33.15 (11.27)	– –	30.33 (10.21)
No. of warning alarms*	101.80 (33.67)	–	92.58 (37.45)	* –	79.58 (43.19)
No. of exceed alarms**	89.15 (36.44)	**	43.50 (31.22)	** –	25.10 (29.20)
No. of automatic recoveries**	1.23 (1.73)	**	0.18 (0.45)	** –	0.05 (0.22)

Asterisk (*) or double asterisk (**) following a name of performance measure indicates that the measure is statistically significant at 5% or 1% level respectively in display group factor.
Column on the left of PGA column shows the results of pairwise comparison between PG and PGA (*significant at 5%; **significant at 1%).
Column on the left of PGA2-R column shows the results of pairwise comparison between PGA2-R and PG (top row), and PGA2-R and PGA (bottom row) (*significant at 5%; **significant at 1%).
Three measures (Goal_reach time, Diagnosis time, SSD before goal_reach) were transformed into ranked order (ordinal scale) because these could not be obtained for all the participants under a given task time length (480 seconds).

SSD after goal reach in each problem. The difference in SSD score between the groups shows a consistent pattern in spite of the varying difficulty of the problems.

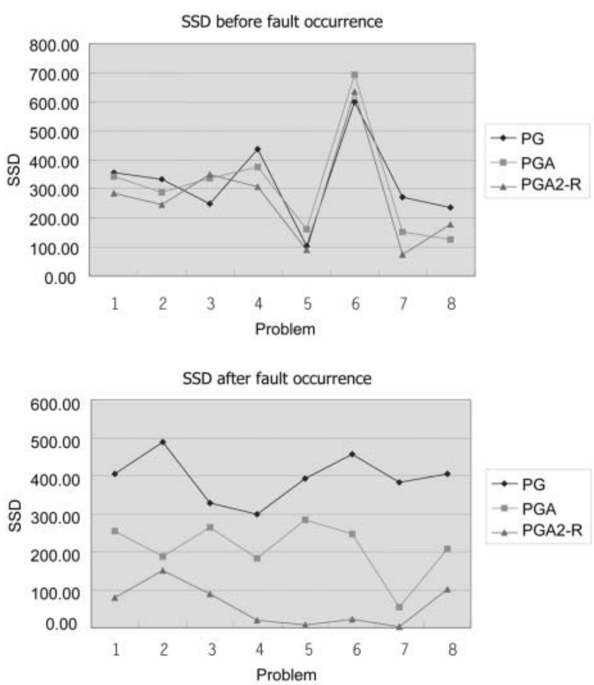

Fig. 9. Average performance in each problem.

PGA2-R enabled significantly better performance in both operational situation (goal_reach time) and diagnostic situation (diagnosis time) compared with the other displays. SSD after fault occurrence shows the most striking differences among the three displays. This also provides a very reliable clue to understanding the other results. SSD should normally decrease very quickly after the goals are reached. This was observed as expected. However, after a fault occurred, SSD in the PG display group increased, while the other display groups maintained low SSD. The PGA2-R group showed by far the lowest SSD in later phases. This implies that the combined task of fault diagnosis and compensating operation was extremely demanding. Thus, the performance difference in operation was greatly increased, as the diagnosis, as the primary task, demanded much mental resources. The PGA2-R display best supported the diagnostic tasks, so that the operators could pay more attention to the operation tasks.

The number of warning alarms, unlike in Experiment 1, lost its significance since the operators, being in a severe situation, did not make an intensive effort to avoid this relatively light risk. Instead, the number of exceed alarms and the number of automatic recoveries showed large improvements when AF-level information was provided.

The PGA display showed better performance than the PG display in the measures of operational stability, especially in the more demanding, fault-existing phases of

Table 10. P_values summarised from ANOVA in Experiment 2

	Goal_reach time	Diagnosis time	# of control actions	# of warning alarms	# of exceed alarms	# of automatic recoveries
Group	0.0252*	0.0043**	0.1141	0.0339*	0.0006**	0.0083**
Problem	N/A	N/A	0.0001**	0.0001**	0.0004**	0.1236
Group* Problem	0.3690	0.6268	0.5576	0.1645	0.4970	0.7498

	SSD total	SSD before goal_reach	SSD after goal_reach	SSD before fault occurrence	SSD after fault occurrence
Group	0.0047**	0.0879	0.0038**	0.4733	0.0011**
Problem	0.0001**	N/A	0.0026**	0.0001**	0.7325
Group* Problem	0.9174	0.0725	0.3149	0.7787	0.9729

*Significant at 5% level; **significant at 1% level.
Three measures in ranked order (Goal_reach time, Diagnosis time, SSD before goal reach) were analysed by Friedman's test (non-parametric method).

the tasks. This confirms that AF-level information has great value in operation tasks. Considering the strong effectiveness of the PGA2-R display both in diagnosis and in operation, though, it is obvious that the presentation of the goal–means relationships was more influential than the mere existence of AF-level information.

The ANOVA results are summarised and shown in Table 10. There were significant differences among display types in the following measures: goal_reach time, diagnosis time, SSD (sum of state deviation) total, SSD after goal_reach, SSD after fault occurrence, the number of warning alarms, the number of exceed alarms and the number of activations of automatic recovery.

The results can be summarised as follows. Under a normal situation without fault, the added AF-level information showed weak effectiveness in the operation task. Its effect was not great in diagnosis either. However, under cognitively demanding situations with faults, AF-level information helped the operator control the system more safely, while diagnosing the fault more quickly.

Information layout according to goal–means relationships greatly increased the effects of AF-level information. The effects were even stronger when the tasks required both fault diagnosis and compensation. This may be partly because the relationships across AH levels could be used for analytical examination of diagnostic information (Rasmussen 1985). Another possibility is that the operators could easily integrate information at the same level since the sets of related data were grouped under the common higher-level information. This can be supported by the results of Burns' (2000) study. She argued that the operator adopted the strategy integrating information along structural decomposition levels within each abstraction level when all the information of AH was provided in the task of fault management.

PGA, PGA2 and PGA2-R displays contained more information content than the PG display, so one might argue that the advantage of the other displays over the PG display was simply due to the additional information. However, as in the study of Yoon and Hammer (1988), more information would not simply result in better performance unless it was additionally helpful. With regard to this point, as Vicente et al (1995) indicated, what is important is whether a design principle helps the designer to identify, parsimoniously, the goal-relevant information that should be included in the interface and properly represent it.

It should also be noted that the participants in the experiments were undergraduate students and this may affect generalisation of the results. Considering that the required expertise level is relative to the complexity of the system and tasks, and that the experimental work domain was much simpler than in a real nuclear power plant, the non-professional participants' performance in the experiments may still permit meaningful interpretation. On the other hand, the use of students helped to avoid the complication due to domain-specific factors such as diverse experience and case-specific diagnostic procedures.

5. CONCLUSION

In this study, two experiments and their results were reported. The experiments investigated the effectiveness of providing AF-level information and presenting goal–means relations between levels of AH in two typical process control tasks, namely fault diagnosis and operation, in an analytical way. Three display types were compared in the experiment. The PG display presented GF-level information with the physical information. The PGA display presented AF-level information in addition to the information on the PG display. PGA2 and PGA2-R displays carried the same information as the PGA display but in a format that explicitly represented the goal–means relationships between higher-level and lower-level abstract information.

The experimental results showed that AF-level information was additionally effective on a display that already had physical information and GF-level information. The effect was most pronounced when the task situation was cognitively demanding, such as the cases of complex diagnosis and compensating operation. The representation of goal–means relationships and information layout according to them greatly increased the effectiveness AF-level information. The results add support for the EID concept that providing abstracted functional information based on the work domain analysis according to abstraction hierarchy is an effective approach for designing information content and structure.

Function analysis and information design based on goal–means hierarchy have advantages that may be generalised in various situations. In systems that are more complex than the experimental work domain of this study, there may exist multiple-layered hierarchies. The goal–means relationships may well become *n*-to-*n*, while a simplistic tree structure contains only 1-to-*n* relationships. The difficulty of the work domain analysis along the AH will naturally grow. In such a situation, however, the reward of an explicit and systematic goal–means analysis will increase much more steeply. The designer will benefit from the increased awareness of the functional structure since display design relying on intuition or implicit personal knowledge will hardly be successful in such cases.

Other circumstances to consider are cases of unexpected situations during operation. In such situations, operators should adopt a knowledge-based behaviour mode, relying more on their principle knowledge about the system rather than predefined task procedures (Yoon and Hammer 1988; Vicente and Rasmussen 1990). It is one of the main principles of EID that knowledge-based behaviour should be supported by embedding an AH representation in the interface. The operator will be aided by the externalised mental model of plant dynamics, especially during abnormal situations requiring problem solving.

Three design principles for information display are derived from the results and experience of the experiments. The first is that designers should systematically identify and organise information along the goal–means relationships to design an effective information display. The second is that goal–means relationships between higher-level and lower-level information should explicitly be represented in order to support resource-demanding tasks. The third is that the information layout should accommodate information integration along a structural aggregation–decomposition dimension at each abstraction level. Goal–means analysis is helpful in defining a proper information layout for this purpose.

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Nomenclature

CIV:	condensation isolation valve
CON:	condenser
COS:	condensation system
CP:	condensation pump
FCV:	feedwater control valve
FIV:	feedwater isolation valve
FP:	feedwater pump
FSS:	feedwater supply system
GEN:	generator
HPH:	high-pressure heater
HPT:	high-pressure turbine
LPH:	low-pressure heater
LPT:	low-pressure turbine
LPTIV:	low pressure turbine isolation valve
PWR-NPP:	pressurised water reactor nuclear power plant
SDV:	steam dump valve
SG:	steam generator
SGS:	steam generation system
SIV:	steam isolation valve
TCV:	turbine control valve
TOS:	turbine operation system