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The Analytic Design Application of the Cognitive Interface for a Digitalized Control Environment

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Abstract: This study aims to show the feasibility of the application of Ecological Interface Design (EID) method that may improve operator performance in digitalized system environment such as main control room in next generation nuclear power plant. While cognitive interface design method such as Information Rich Display (IRD) is mainly focused on stereotyped information for the user, EID method helps user's mental resources to be allocated to tasks that process highly abstract information including diagnosis and situation assessment. However, the sophisticated and relationship-embedded EID displays may cease to be intuitive when many of them are presented without consistently designed common elements. This study showed the suggestion of the consistent elements of EID displays for a digitalized main control room of nuclear power plant taking the example of the control process of Steam Generator (SG) water level. The proposed EID displays were reviewed by domain experts and operators to conjecture how such EID displays might benefit the operator's decision making. The experience from this study indicates that situation awareness in digitalized interface design may be improved by appropriately designed visualization of abstract information and that operator may be aided by the represented dynamics in EID display.

Key words: Cognitive systems engineering, display design, ecological interface design, work domain analysis, abstraction hierarchy, Steam Generator (SG)

INTRODUCTION

Complex human machine systems such as nuclear power plant and avionic system tend to adopt more and more digitalized human-machine interfaces such as computer based procedure, large display panel and workstations with soft-control to help the operators make operational decisions more efficiently. The analog or partly digital-typed interface of Main Control Room (MCR) in Nuclear Power Plant (NPP) is gradually being replaced by the totally digitalized interface suitable for the digital environment. The main control room of SKN 3 and 4 NPP in Korea is among such examples (Fig. 1).

A digitalized system and as the information should be displayed on relatively limited space, the level of cognitive complexity, hence, mental workload in managing the human-system interaction is being increased. Human operators also tend to show over-reliance to the automated system which was developed to reduce human errors from the misuse of the digitalized interface different from the stereotyped one. In fact, the more the computerized devices and procedures are used in the system, the mental model of computer users has been more changed from analogue stereotype to digitalized one (Cha, 2010).

Fig. 1: Example of a totally digitalized MCR

All the information to be processed in a digitalized system cannot be displayed on the limited interface space, so that, crews make a decision relying on mental resources for abstracted information. For reducing the mental workload, the cognitive interfaces seem to work well by visualizing and displaying the abstracted information on the human machine interface. Cognitive interface suggests that the higher-order functional constraints governing the process be made directly available to operators in a manner allowing them to pick up that information using their cognitive capabilities.

Cognitive engineers have used two theoretical frameworks to design a cognitive interface; Information Rich Design (IRD) and Ecological Interface Design (EID). While Information Rich Display (IRD) is mainly focused on providing stereotyped information to the user, EID method effectively enables operator's mental resources to be concentrated on highly abstract information-based tasks such as diagnosis and problem solving. Being a relatively new approach to designing user interfaces, EID has been focused on the Human-Machine Interfaces (HMI) for large-scale dynamic systems such as power plants, aircrafts and ships. In EID methods, combined are the analytical tool of the abstraction hierarchy, human decision making strategies and the insights of SRK taxonomy. The resulting design provides more intuitive and direct information to the human decision making tasks. The design is also expected to be more robust in unanticipated situations (Vicente, 2002).

A sophisticated unit of EID display represents multiple-level information by figuratively organizing the low-level variables involved. Conveying both the high-level information and its low-level components at the same time, the underlying relationships are easily perceived and intuitively understood. Eyes then trace the implied relations to utilize whichever level of information that is more directly useful in human decision making at a time.

Paradoxically, an almost inevitable drawback of EID comes from this sophistication. As many units of EID displays are presented, the complex and inventive figures may interfere with each other and become confusing. To cope with this problem, consistency should be introduced and observed. Not only the elementary representation of variables but also the ways in which relations are signified should be designed with consistency.

This study describes an effort to suggest a set of consistent elements of EID displays for a digitalized main control room of nuclear power plant taking the example of the control process of Steam Generator (SG) water level.

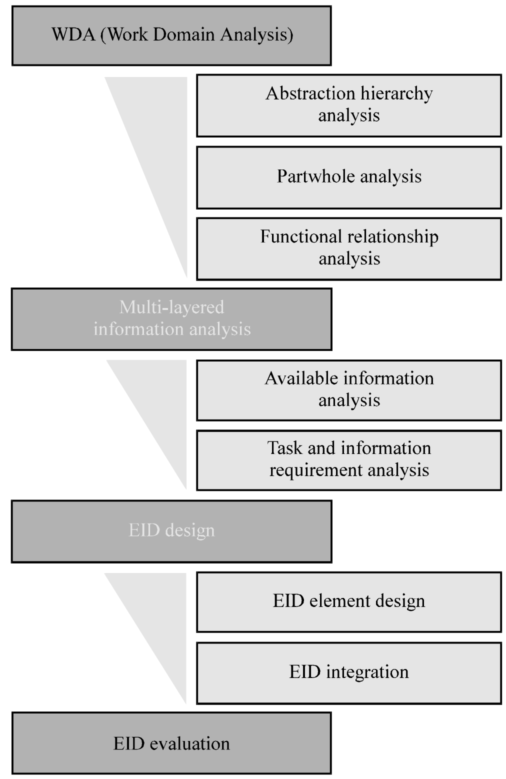

Fig. 2: EID design process

MATERIALS AND METHODS

EID design process

Work Domain Analysis (WDA): The EID design process starts with Work Domain Analysis (WDA) and proceeds with information analysis and EID element design and integration (Fig. 2). WDA uses Abstraction Hierarchy (AH) as a fundamental scheme to analyze the dynamic environment or the work domain. Abstraction levels are reflecting goal-means relationship. Starting with the purpose level at the top, it goes down to the levels of abstract function, generalized function, physical function and physical form. Functions at a level have semantic representations and relationships that are characteristic at the level. Thus, functional organization should be identified for each level of abstraction. For example, the functional organization analysis when performed at the physical function level, would provide a diagram that is similar with the schematic in the large display panel in the control room. AH analysis may be performed at various levels of detail according to a part-whole hierarchy but the functional organization analysis at each AH level achieves important parts of the purpose of the part-whole analysis.

Information analysis: Information analysis phase connects WDA and EID design phases, translating the functional description produced by WDA into information description that is required in actual EID design. As in the WDA phase, the information analysis is also performed in multiple layers according to the AH. An information item that appears at a higher level of abstraction is usually related to one or more items at the lower level which are summed up to the higher level information item. These relationships are what the EID should attempt to preserve visually in the display.

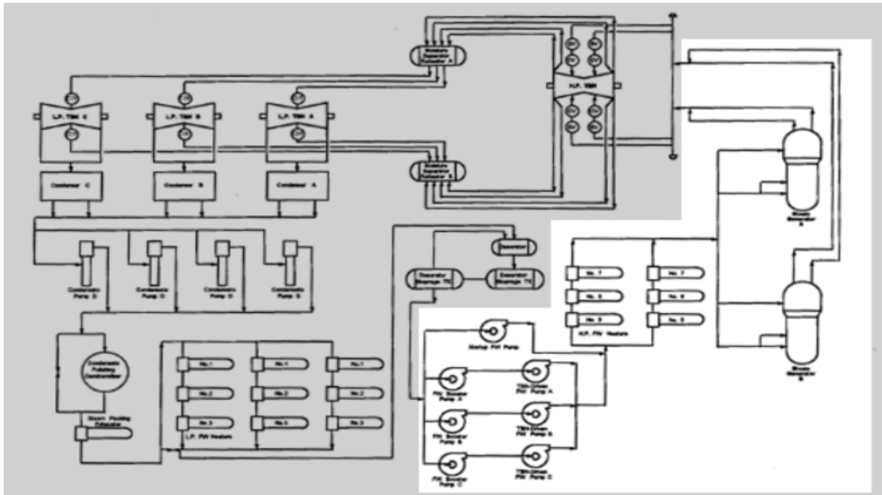

Fig. 3: Main feed water system

Another source of EID's visual relationships is the causal or grouping relationships among information items that may be identified on the basis of the functional organization at each AH level. These relationships when they are considered in human reasoning during tasks that use the information items should be visually represented to aid the inference.

The first step of the information analysis is to enumerate all the available information (Hajdukiewicz and Burns, 2004). Starting from the physical sensors, the analyst will identify all the information items that the sensors are able to deliver. Continuing with higher level function, more complex or processed information items are identified and listed. The list for a function may include simple sensor readings, abstract information from multiple sensor readings or logically derived information from other functions but defined with regard to the function.

Then, it should be investigated how the information items and their relationships are to be used by the operator. Task analysis such as HTA (Hierarchical Task Analysis) and strategy analysis are conducted for this purpose. The results are used to determine how and when the information should be presented in the display.

EID design: We propose that the EID design process be conducted in two stages: EID element design and integration. The morale is that consistency in elementary representation of relation patterns should be assured first. Then, the EID units can be progressively integrated to express information for larger functions. Sheer inventiveness may produce a very clever and effective EID display but many such displays side by side for different functions would be very hard for the operator to understand and handle. The operator should be aided not only be visual momentum but also what we might call representational momentum.

Analysis and design

Defining the system: The scope of the system employing the cognitive interface to be designed was confined to display a control process of Steam Generator (SG) water level on main feed water system in a digitalized main control room of nuclear power plant (Fig. 3).

Abstraction Hierarchy: From the WDA of SG in order to design the interface for maintaining water level of SG, two Functional Purposes (FP) were selected: 'Maintain water level' and 'Avoid Accident'. From the purposes, Physical Functions (PFn) were listed including pump, valve, u-tube, pipeline, heater, level indicator. Physical Form (PFm) included colour and shape of the PFn. Based on the PFn, included General Functions (GF) were activate pump, heat increase by heater, flow, open-close valve, heat increase by u-tube, transform liquid and gas and steam flow. The variables and processes are shown in Fig. 4.

Information requirement: The WDA was conducted at various levels of detail along the part-whole hierarchy of system-subsystem-components (Fig. 5). Extracting information requirements from an AH involves converting the work domain model into a list of variables of SG.

Hierarchical task analysis was performed with a well-organized in-use operational procedure, EOP to confirm the information requirement obtained from WDA including a flow, pressure, temperature and water level. The specific procedures of Emergency Operation Process (EOP) included LOCA (Loss of Coolant Accident), SGTR (Steam Generator Tube Rupture) and reactor TRIP which were related to information requirement from WDA.

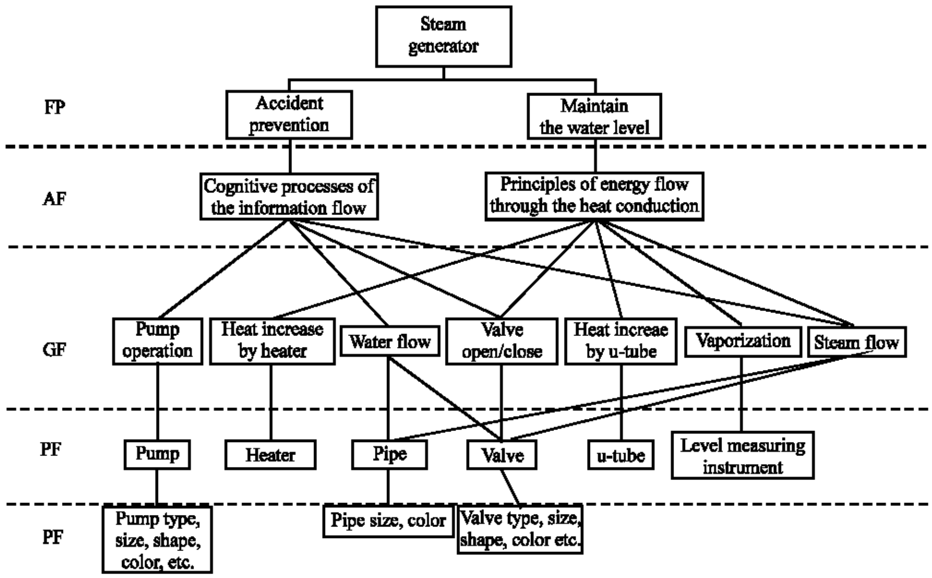

Fig. 4: Abstraction hierarchy of SG

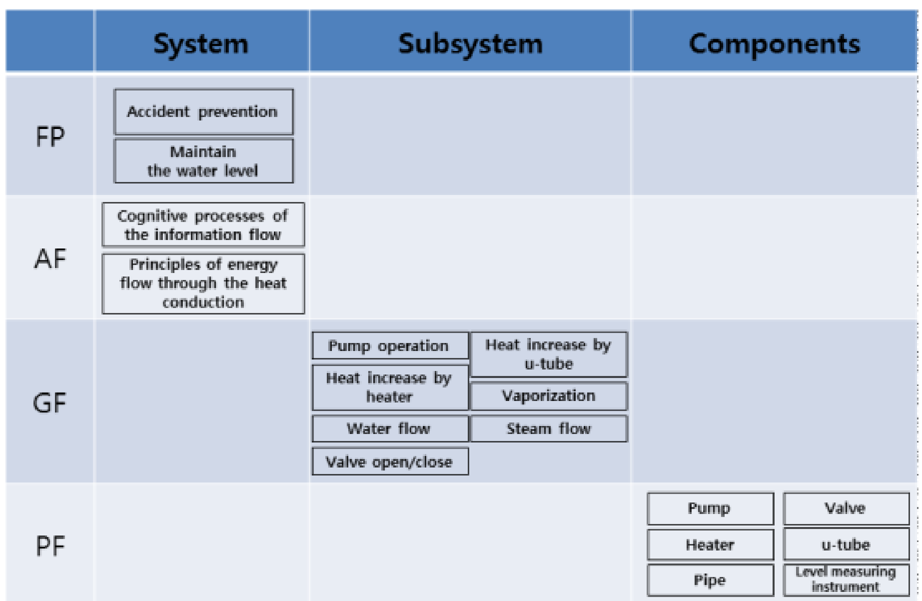

Fig. 5: Part-whole decomposition of SG

Information displays: From the results of WDA and task analysis (HTA), cognitive oriented displays were developed based on EID principles. The display elements were categorized into 3 classes: single variables, multiple variables and integrated template.

Individual interface represents the system component. Single variable represents the values, trends, derivation and reference point of variables (Fig. 6). Multiple variables represent the relationship between variables (Fig. 7).

Integrated EID display: Conventional displays for SG were surveyed before integrating the EID elements into a comprehensive EID for SG (Fig. 8). The conventional displays of SG contained familiar P&ID (piping and instrument diagram) mimics to actual operators and used for comparing with the proposed EID displays.

The proposed SG display was developed based on the elementary EID units and task analysis result (Fig. 9). The interface visualizes the abstracted information in relation with its component information of which relations were obtained from WDA and hierarchical task analysis.

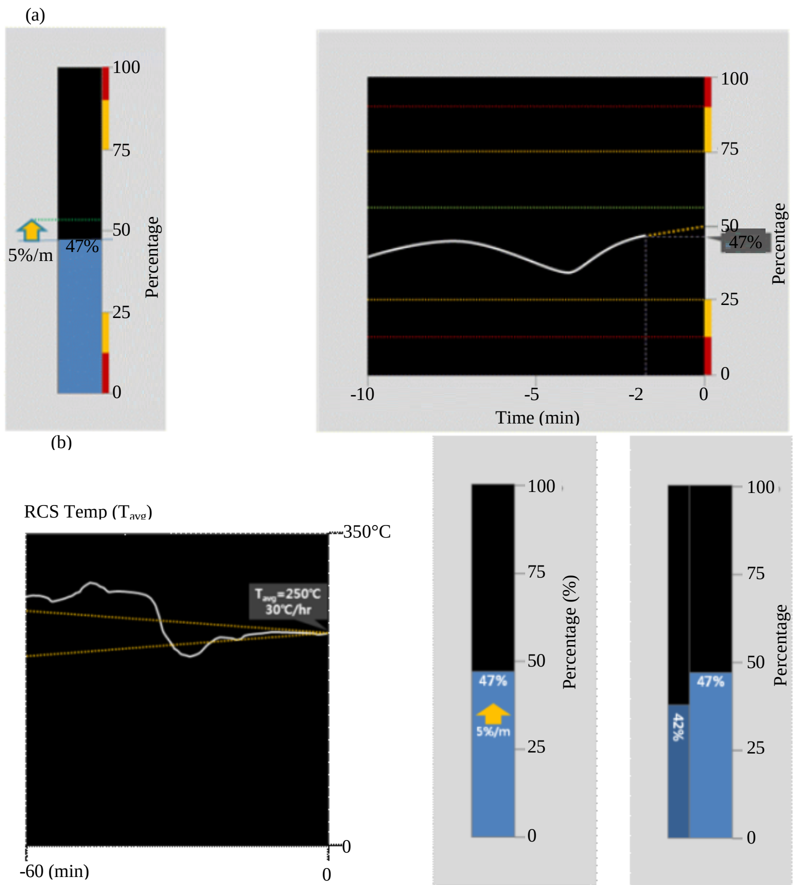

Fig. 6: a, b) Single variable displays

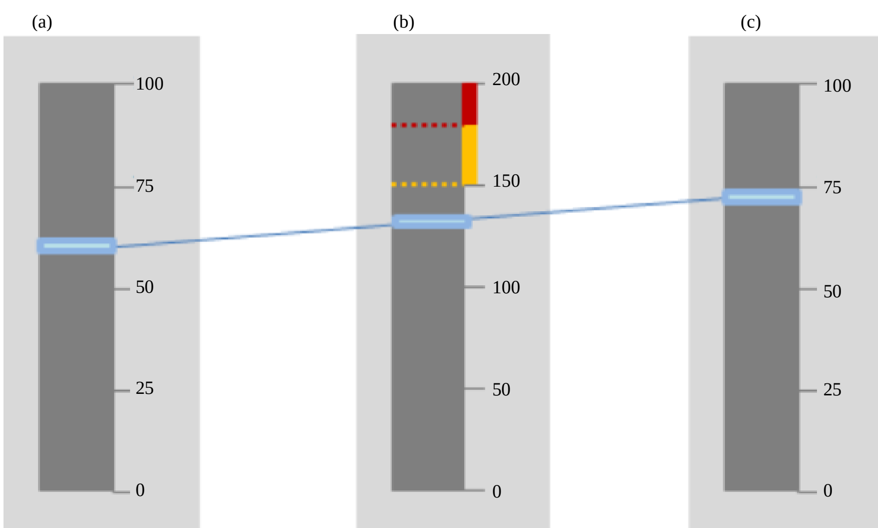

Fig. 7: a-c) Multiple variable displays

Figure 9 shows an example of integrated EID display for SG control system. The layout implies the flow direction of the feedwater (i.e., right to left) and the abstraction levels (i.e., left is higher at the top row. Although, the complexity of unit displays is not as high as some typical EID examples and thus, the density of information packed in a Fig. 9 is moderate, the consistent element design for the building components provide easy and comfortable overall display.

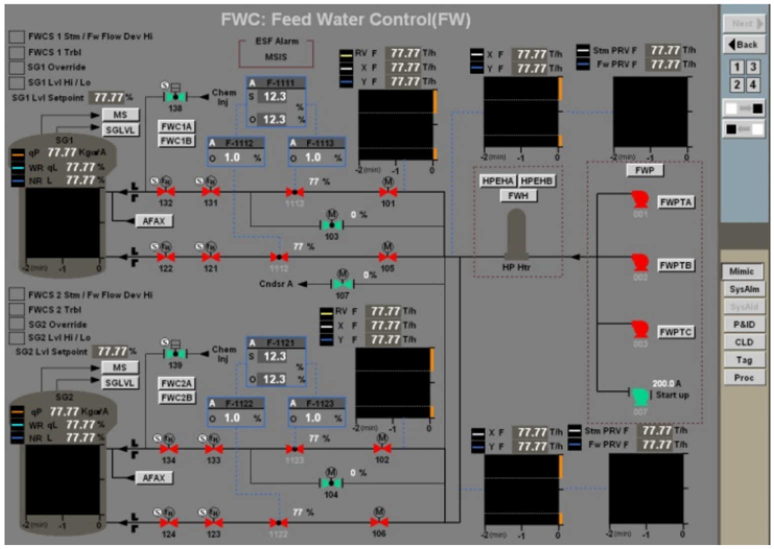

Fig 8: A conventional display of Steam Generators (SG)

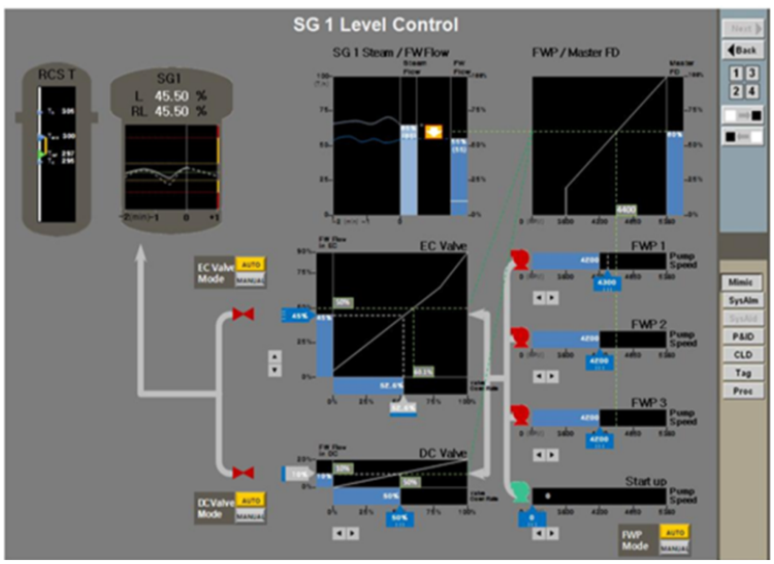

Fig. 9: Proposed example of EID for SG process

RESULTS AND DISCUSSION

EID display review and suggestions: As the EID example was not developed as a simulation, only a qualitative expert review was conducted. The display was not designed with an aim to replace current display altogether but to be used as a complementary one. One of the reservations was that in an emergency situation, there would be no guarantee that the surrounding subsystems are all in normal working conditions. The conventional P&ID display would provide overall system architecture to support wide-range diagnosis. However, modern MCRs provide a large main display both in the main panel (Fig. 1) and operator's consoles. Then one of the screens in front of each operator already provides task-oriented displays such as EID as well as system-oriented displays. That is the EID displays would not replace the overall main schematics or the system-oriented displays of subsystems but reorganizes the task-oriented displays. Then the question is how the EID displays maintain mental momentum when the operator transit between the EID to system-oriented displays or between different EID displays. In purely system-oriented views, it is relatively easy to support such cognitive momentum, since, visual momentum naturally warrants it.

Among the suggestions collected, 3 important points are worth noting. First, to the experts some information is more crucial than the others. The amount of information provided and its salience should be proportional to the informational importance to guide proper attention of the operator. An EID tends to provide too much detailed information, so that, important information items may be obscured by the numerousness and complexity. This is where the EID designer has to pay extra attention.

Second, highly trained operators are accustomed to get numbers, rather than figures and control the system using the numbers. To support, exact numbers of important variables should be more conspicuous in the display. This is indeed a subject that EID philosophy dealt with form the first by considering SRK frame that is skill-based, rule-based and knowledge-based behaviours. Therefore, it is not a weakness of EID approach but an information requirement to be considered more explicitly.

Third is a problem that is more general in digitalized systems. Soft controls are not as intuitive to handle as their tangible counterparts and tend to cause more errors. How the EID can be combined with the operation controls is a question for the EID designers and a subject that requires further experimental research to make EID practical alternative to conventional displays.

CONCLUSION

This study describes the design of consistent and easy-to-integrate EID display units in nuclear power plant domain. There were many research evidences for the cognitive benefits to use EID instead of conventional interface (Ham and Yoon, 2001; Hajdukiewicz and Vicente, 2002; Burns *et al*., 2008). The abstracted information on a cognitive interface may reduce possible mental workload, enhance monitoring and situation awareness and support diagnosis in a digitalized system environment. It is of a particular interest that EID was reported to improve situation awareness during the monitoring to deal with unanticipated events (Vicente, 2002). With all the benefits suggested in academic studies, the innate complexity and possible inconsistency in representing relationships among variables in visual forms hamper practical implementation of EID in real systems where safety is usually the utmost concern. This research proposed an design approach to assure the cognitive consistency by first developing elementary EID units in a stepwise manner: from single-variable displays, multiple-variable displays and then integrating templates.

An exemplar EID design was shown for SG control process in the nuclear power plant. It is intuitive and easy to learn and use. Moreover, the design is extendible to the other subsystems without changing elementary information manifestations and the way they are integrated. As more evidences are collected for the usefulness and robustness of such elements and as more technical solutions appear to overcome current weaknesses in EID design to complete the cycle of monitoring and control, the benefits of EID will be fully realized in practical systems.

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