Allocating Human-System Interfaces Functions by Levels of Automation in an Advanced Control Room

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Abstract. Human factors engineering (HFE) focuses on the design of human-system interfaces (HSIs). The HSIs, those NPPs parts that personnel interact with in performing their tasks, included control switches, red, green, amber, and white indictor lights, mimic displays, lighted annunciator panels, and hand-written status boards. The advanced technology has introduced the capability of integrating information from numerous plant systems and supplying needed information to operations personnel in a timely manner. Challenges of the well-integrated computerized control room include ensuring reduced staffing does not treat with increased task complexity, achieving a consistent user interface, ensuring increased automation does not adversely affect the operator's mental model of the plant, and systems actually support the operator. This study investigated the process of the HSI functions allocation by considering which functions should be automated and to what extent, which is also called the level of automation (LOA).

Keywords: Human factors engineering, human-system interface, nuclear power plants, type of automation, level of automation.

1 Introduction

The staff of the US Nuclear Regulatory Commission (USNRC) is performing nuclear power plant (NPP) design certification reviews based on a design process plan that describes the human factors engineering (HFE) program elements to develop an acceptable detailed design specification and an acceptable implemented design. The HFE Program Review Model (HFE-PRM) [1] was developed as a basis for performing design certification reviews that include design process evaluations as well as review of the final design. The HFE PRM consists of ten elements: HFE program management, operating experience review, functional requirements and allocation analysis, task analysis, staffing, human reliability analysis, human-system interface (HSI) design, procedures development, training program development, and verification and validation. This design review approach was used in several advanced reactor HFE reviews [2].

J.A. Jacko (Ed.): Human-Computer Interaction, Part IV, HCII 2009, LNCS 5613, pp. 741–750, 2009.

1.1 Functional Allocation

Functional allocation, which is also called allocation of function (AOF), is one of these critical HFE PRM elements. AOF is the process of allocating tasks to humans and machines in a way that adds value to the capability in terms of cost, safety and performance. Decisions of AOF provide an essential foundation for the identification of system requirements, and for design process (e.g. workstation and HSI design). Human factor inputs in the element are required to increase the understanding of human capabilities and constraints, workload limitations and human-computer interaction issues. All of these factors need to be identified and traded-off against each other to arrive at the optimal allocation of function between the humans and machines.

The AOF decision-making process should first consider all possible ways that functions could be implemented. These possibilities should be documented and tabulated in a way that shows three alternative solutions: Human, Machine, and Human-Machine. Criteria should be established in terms of cost, performance, reliability, maintainability, personnel requirements, safety, user preference, limitations, workload, etc [3]. These criteria should be used to determine the optimal allocation of each function. Methods and tools include: job or flow process charts, function allocation evaluation matrix, role of the person, function allocation tool, roles of humans & automation, integrated computer-aided manufacturing definition.

Successful AOFs are realized when the human and machine are given best allocation consideration. While the AOF change, such as automation, the roles of human operators in the system have also been shifted from a direct manual controller to a supervisory controller and system monitor who are largely removed from direct control. As described in variety of guidance, automation should be used to protect society from the fallibility and variability of humans. This requires a detailed task analysis that is proposed for a human, including the possible errors and the possible consequences. Further, automation should be used to reduce human cognitive overload. Humans can be ill with from information overload and consequent mental overload. This can occur from high information rates, competing tasks, or task complexity. For example, system operators working with automation have been found to have a diminished ability both to detect system errors and subsequently to perform tasks manually in the face of automation failures, compared with operators who manually perform the same tasks [4]. The above situation is named as the ‘out-of-the-loop’ (OOTL) performance problems.

1.2 Level of Automation

Human-centered automation, as proposed by Billings [5]; [6], is a famous approach for avoiding OOTL performance problems by optimizing the human-automation function allocation. Billings [5]; [6] considered human-centered automation a philosophy that facilitates a cooperative relationship in control and management with potential performance benefits. Some researchers proposed their concepts to realize this philosophy, such as the level of automation (LOA).

The LOA can be defined as the level of task planning and performance interaction maintained between a human operator and computer in controlling a complex system

[7]. These studies on the LOA [8], [9] have developed theoretical frameworks for HIP functions regarding what complex system functions should be automated, and to what extent. Building on the taxonomy of Endsley and Kaber [8], Kaber and Endsley [10] assessed the performance, situational awareness (SA), and workload effects of low, intermediate, and high LOAs using a simulated control task. Their results demonstrate that LOA is a crucial determinant of primary task performance and SA. Furthermore, they also found that low-level automation produced superior performance and intermediate LOAs facilitated higher SA. Their research was performed in a controlled laboratory setting using a simulated task to develop general results applying to numerous domains.

Without a doubt, automation may contribute to reducing operator workload and fatigue, improving safety, and facilitating faster and more accurate control of multiple simultaneous tasks, it can also lead to problems in the interaction between operators and automated systems [11]. These problems include reduced operator system awareness, increased monitoring workload, and reduced manual skills. Although considerable body of literature exists on the effects of automation, there is a surprising lack of information regarding the influences of LOAs on the HSI design in the ACR and providing a framework for preventing human errors. Therefore, this study proposed a process to investigate how to allocate HSI functions by appropriate LOA in an ACR.

2 Related Issues of the HSI Function Allocation in an ACR

2.1 Regulatory Requirements and Guidelines

The HFE-PRM [1] used by the staff of the US Nuclear Regulatory Commission to review the HFE programs of applicants for construction permits, operating licenses, standard design certifications, combined operating licenses, and for license amendments. The purpose of these reviews is to verify that accepted HFE practices and guidelines are incorporated into the applicant's HFE program. In this section, this study discussed the related issues of HFE-PRM.

Functional requirements analysis is the identification of those functions which must be performed to satisfy the plant's safety objectives, i.e., to prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. Function allocation is the analysis of the requirement for plant control and the assignment of control functions to (1) personnel (e.g., manual control), (2) system elements (e.g., automatic control and passive, self-controlling phenomena), and (3) combinations of the two (e.g., shared control and automatic systems with manual backup).

Task analysis is the identification of task requirements for accomplishing the functions allocated to plant personnel, such as (1) provide one of the bases for making decisions on design, (2) verify that human-performance requirements do not exceed human capabilities, and (3) from the basis for specifying the design requirements for the displays, data processing, and controls needed to carry out tasks. The HSI should be designed using a structured methodology that should guide designers appropriately translating functional and task requirements to the detailed design of alarms, displays, controls, and other aspects of the HSI.

Except the HFE-PRM, the NRC staff will use the methods described in this Interim Staff Guidance (ISG) [12] to evaluate licensee compliance with USNRC requirements as presented in submittals in connection with applications for standard plant design certifications and combined licenses. This ISG provides acceptable methods for addressing the highly-integrated control room-human factors issues (HICR-HF) in the digital I&C system designs. Minimal inventory of the HSIs is an important topic and should be considered in the HSI design. The minimal inventory of HSIs (i.e., alarms, displays, controls) needed to implement the plant's emergency operating procedures, bring the plant to a safe condition, and to carry out those operator actions shown to be risk important should be described.

Due to the regulatory requirements and guidelines, to allocate HSIs functions by the LOA in an ACR is a critical way to achieve the plant's safety objectives. While accomplishing the excellent HSIs functions allocation, the detailed design of alarms, displays, controls will meet the task requirements. Then, these task requirements can achieve the safety functions assigned to humans, as shown in Figure 1.

2.2 Allocating HSI Functions by LOA in an ACR

(1) Functional Requirements Analysis and Function Allocation
In this stage, those functions which must be performed to satisfy the plant's safety objectives should be identified. Then the initial analysis of the requirement for plant control and the assignment of control functions to personnel, system elements, or combinations of the two by considering cost, performance, reliability, maintainability, personnel requirements, safety, user preference, limitations, and workload should be made.

(2) Type of Automaton and Level of Automation
Parasuraman et al. [9] proposed a model for types and levels of automation. The theoretical basis for classifying types of automation (TOAs) is offered by the four stage human information processing (HIP) model [13]. The model proposed by Parasuraman *et al.* [9] can cover the automation of different types of functions in a human machine system, including information acquisition, information analysis, decision-making and action selection, and action implementation. Endsley and Kaber [7], [8] addressed the classification of automation into four cognitive and psychomotor aspects of HIP, including monitoring display, generation of processing options, selection of an 'optimal' option and the implementation for this option. The taxonomy of Endsley and Kaber's TOAs provided a wide range allocation of system functions to human, computer, and human/computer combinations.

(3) Initial Task Analysis
The aim of the initial stage of task analysis is to collect and organize the information (data) in a meaningful way, such that subsequent to analysis, the information is easily and efficiently used for a variety of purposes (e.g., training requirements, training content, design and design review, etc.). Specifically, the goal of this task analysis is design; therefore, information management is structured toward that end. In order to define the optimum man-machine interface based on the requirements made evident by the inherent predictive nature of this task analysis.

(4) Detailed Task Descriptions

In the engineering design process, a task is defined as the collection of activities performed by a person or by a machine directed toward achieving a single sub-function. The product resulting from the task analysis applied to those functions allocated to humans is basic for developing detailed task descriptions that address: information requirements; decision-making requirements; response requirements; feedback requirements; associated task support requirements; workplace factors; staffing and communications requirements; hazard identification; personnel workload.

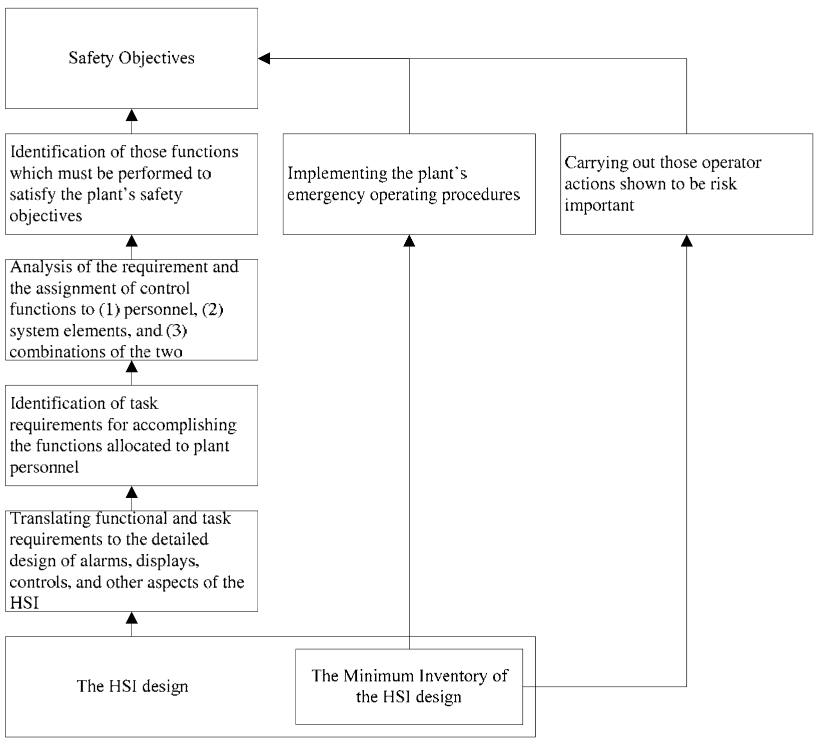

Fig. 1. Relationships between safety objectives and the HSI design

(5) Human System Interface Design

The HSI meet the technical requirement (i.e., reliability, operating experience, etc.) as required by the task analysis design requirements, operator evaluation, and applicable plant procedures (e.g., operating, abnormal, emergency, etc.). The design evaluation is based on the objectives of the systems design. What should the system do, who will use it, where will it be used and when will it be used. If the objectives are clear, the evaluation of the results will be made simpler.

3 A Case Example of the HSI Function Allocation in an ACR

3.1 System Design Description

The target system discussed here is about rod control and information. The detailed system descriptions are explained as the following.

(1) Controls changes in the core reactivity, power and power shape.
(2) Displays summary information to the plant operator about positions and status of the control rods.
(3) Provides control rod position and status information to other systems in the plant.
(4) Provides for both manual and automatic insertion of all control rods, by an alternate and diverse method.
(5) Provides for both manual and automatic insertion of selected control rods for core stability control.
(6) Prevents potentially unsafe rod movements by automatically enforcing rod movement blocks.
(7) Provides for performing planned surveillance tests.
(8) Prevents any further rod withdrawal movement in the presence of a rod withdrawal block signal.
(9) Provides part of the controls and protection features to assure that the single rod drop event is an incredible event that does not need to be analyzed or tested.

3.2 Functional Requirements Analysis

This functional requirements analysis has been performed to define the system functions, system processes, system process elements, system performance requirements and system support requirements for the target system. None of the functions analyzed are safety related. Three modes of operating modes include in the system:

(1) Automatic rod movement. The automatic mode provides for automatic ganged rod selections and movements.
(2) Semi-Automatic rod movement. The semi-automatic mode allows the operator to automatically select and move the next gang or rods (as appropriate). Rod movements can be performed manually carried out by the plant operator.
(3) Manual rod movement. The manual mode provides for manual rod selection and movements under the direct command of the plant operator. The operator's selection of any specific rod in the gang automatically results in the selection of all other associated gang members of that rod.

3.3 Allocation of Functions

This AOF analysis for the target system supports the design of the HSI. Its conclusion is that the control actions allocated to the human can be properly performed by humans, considering that the machine performs the actions allocated to it, as shown in Table 1 and Table 2.

(1) Initiation. To take the decision and/or to initiate the performance of the function by the machine or the human or both.
Assigned to the machine. It is the function initiation through automatic or interlock signal coming either from this system or another.
Assigned to the human. It is the function initiation accomplished by the operator through push-button, key switch or another similar device in the main control room. (MCR man machine interface device).
Assigned to the combination of human and machine. Automatic and manual operations combined in the initiation of a function.

(2) Performance: This is the accomplishment of the actions to achieve the alignment allowing the fulfillment of the function.
Assigned to the machine. It involves the automatic fulfillment of the actions, on the components, in order to accomplish the function.
Assigned to the human. It involves the operator manual fulfillment, in the MCR, of the necessary actions on the components, in order to accomplish the function.
Assigned to the combination of human and machine. Automatic and manual operations combined for the fulfillment of a function.

(3) Verification: Set of actions performed by the machine or the human in order to verify that the function is achieving its purpose or, on the contrary, if it is no longer required. This is the system response checking.
Assigned to the machine. It involves the automatic verification of components and parameters for all control actions related to a function or function segment.
Assigned to the human. It involves manual verification of components and parameters for all control actions related to a function or function segment.
Assigned to the combination of human and machine. Automatic and manual operations combined for verification of components and parameters for all control actions related to a function or function segment.

(4) Terminate: Set of actions performed by the machine or the human to finish the function performance.
Assigned to the machine. It involves the automatic fulfillment of the actions on the components, for the conclusion of the function.
Assigned to the human. It involves the operator manual fulfillment, in the MCR, of the necessary actions on the components, for the conclusion of the function.
Assigned to the combination of human and machine. Automatic and manual operations combined for the conclusion of a function.

Table 1. Part of the system functions and operating modes

Function Identification	Operating Mode Identification	
Core reactivity changes control	OM01	Automatic rod movement mode
	OM02	Semi-automatic rod movement
	OM03	Manual rod movement

Table 2. Hypothetical allocation of system overall control actions

Mode ID	Operating Mode Title	Control Actions	Machine	Human	Combination
OM01	Automatic	Initiation Performance Verification Terminate			
OM02	Semi-automatic	Initiation Performance Verification Terminate			
OM03	Manual	Initiation Performance Verification Terminate			

Table 3. LOAs taxonomy (Endsley and Kaber, 1999)

	Roles			
LOA	Monitoring	Planning	Selecting	Implementing
1	Human	Human	Human	Human
2	Human/Computer	Human	Human	Human/Computer
3	Human/Computer	Human	Human	Computer
4	Human/Computer	Human/Computer	Human	Human/Computer
5	Human/Computer	Human/Computer	Human	Computer
6	Human/Computer	Human/Computer	Human/Computer	Computer
7	Human/Computer	Computer	Human	Computer
8	Human/Computer	Human/Computer	Computer	Computer
9	Human/Computer	Computer	Computer	Computer
10	Computer	Computer	Computer	Computer

3.4 Level of Automation

At this stage, one can ask what LOA should be applied. The 10-level taxonomy of LOA was implemented here that is intended to have applicability to a wide array of cognitive and psychomotor tasks requiring real time control [8]. As shown in Table 3, multiple levels of automation can be considered for the combination of four TOAs.

3.5 Task Analysis

By performing the task analysis, the following goals are achieved:

(1) Develop operational sequence diagrams for the tasks to be performed by the operators when interacting with the system, in order to achieve the control functions allocated to them and estimate operator workloads.
(2) Identify critical tasks and risk-important human actions
(3) Identify the general inventory and minimum inventory of alarms, displays and controls (hardware and software) necessary to perform control room tasks, paying special attention to those required to perform critical task and risk-important human actions.

(4) Identify those tasks which require, during their performance, operator communications with personnel outside the main control room (MCR).
(5) Identify operator aids that could be needed by the operators when performing their job.

3.6 Human System Interface Design

This human-system interface design has been performed to define the information, controls and alarms that must be contained in the MCR video display units, for controlling and monitoring the target system. In addition, all the fixed information control and alarms that the target system has available in panels and consoles have also been identified.

4 Discussion and Conclusions

As existing plants undergo modernization and new plants are designed, modern control and information system technologies are being employed. However, some uncertain problems, such as the roles of human and automation, existing in instrumentation, control systems, and control rooms are continuous investigated by researchers. To solve the above problem, this study defined requirements for the HSI functions allocation in an advanced control room for nuclear power plants and investigated the process of the HSI functions allocation by considering which functions should be automated and to what extent, which is also called the level of automation (LOA). Further, a case example of the HSI function allocation in an ACR was used to describe the process.

The process explained by this study can provide a direction for the HSI designer in the stages of HSI plan, analysis, and design. It is expected the process may improve operational safety of HSIs in an ACR. Due to the limitation of techniques, this study does not evaluate the performance for allocating HSI functions by LOA using a simulated experiment at the present time. For ensuring operating safety of the ACR in NPPs, it would be critical and valuable to study the effects of allocating HSI functions by LOA in the future study.

Acknowledgement

This paper is financially supported by a project from the National Science Council of Taiwan under contract No. NSC- 97-2221-E-033 -033 -MY2.

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