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A model-based framework for the analysis of team communication in nuclear power plants

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ABSTRACT

Advanced human–machine interfaces are rapidly changing the interaction between humans and systems, with the level of abstraction of the presented information, the human task characteristics, and the modes of communication all affected. To accommodate the changes in the human/system co-working environment, an extended communication analysis framework is needed that can describe and relate the tasks, verbal exchanges, and information interface. This paper proposes an extended analytic framework, referred to as the H–H–S (human–human–system) communication analysis framework, which can model the changes in team communication that are emerging in these new working environments. The stage-specific decision-making model and analysis tool of the proposed framework make the analysis of team communication easier by providing visual clues. The usefulness of the proposed framework is demonstrated with an in-depth comparison of the characteristics of communication in the conventional and advanced main control rooms of nuclear power plants.

1. Introduction

Communication among co-workers is an essential part of team operation in large-scale complex systems. In the aviation and nuclear power industries, reliable communication is crucial to safety because problems in verbal communication have often led to critical situations.

In the aviation industry, communication error is a major cause of aviation mishaps. A study of the Aviation Safety Reporting System (ASRS) database showed that the proportion of aviation mishaps due to verbal information transfer problems was above 70% [1]. This conclusion led to extensive research into communication as fundamental to human error analysis. Communication errors have been classified with various approaches such as problem types [2], information processing models [3], and standard phraseology [4].

Communication analyses in the nuclear industry can be grouped by the type of main control room. For conventional nuclear power plants (NPPs), crew collaboration and their communication characteristics and portion of communication problems in human error incidents were analyzed [5,6]. In contrast, the communication analyses for advanced NPPs have focused on comparison between advanced and conventional main control room environments [7–9], because the introduction of digital instrumentation and control (I&C) technology, and computerized systems, such as advanced monitoring systems and computer-based procedures (CBPs) in advanced NPPs, has raised new safety concerns including the issue of communication, such as due to changes in the roles of operating staff. The same conclusion has been reached in the study of aviation [10].

When we analyze the relationship between communication error and human error, we have to keep in mind that human error does not itself depend on communication error [10,11], because communication error is only one source of human error. Communication influences listeners' decision-making and behavior by transmitting information about some portion of the cognitive processes of the speaker. Likewise, communication error by a speaker can result in human error by the listener. Thus it is necessary to clarify the function of communication in decision-making and characterize the information transmitted in communication exchanges.

This paper introduces a framework for analyzing the communication between team members during the operation of highly automated large-scale systems. The framework describes the decision-making stages and is based on the observation that human–human (H–H) communication is strongly affected by how information is represented by technical systems.

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2. Advanced control rooms and communication

2.1. The advanced main control room and its characteristics

The advanced main control room (AMCR) is characterized by a higher level of information processing utilizing advanced information techniques and hardware than in a conventional MCR (CMCR), which relies on the concept of single-sensor single-display. This section describes the significant differences between AMCRs and CMCRs and how they affect communication.

Firstly, the information presented by the technical system in an AMCR is different from that in a CMCR. The difference between these types of information can be most succinctly explained in terms of the information level. Along the part-whole dimension, the information presented in an NPP can be classified as belonging to one of the component, sub-system, system, or inter-system levels. Table 1 shows some examples of data that belong to each of these information levels. The information of inter-system level consists of critical safety functions (CSFs), which serve to protect the integrity of one or more of the physical barriers against radiation release of the nuclear power plant. The safety parameter display system (SPDS), which provides the information of CSFs with a concise display, is a part of TMI action items and has already been installed at operating conventional NPPs. AMCRs present information belonging to all four levels by using information processing and advanced graphic displays. Even the component-level information may be presented after processing such as representative value selection or alarm reduction. In contrast, most information in CMCRs belongs to the component level, but some higher-level data (e.g., the SPDS and the Inadequate Core Cooling Monitoring System) were added and used.

However, CMCRs do not operate without any high-level information. For instance, the grouped status lights for Bypassed and Inoperable Status Indication (BISI) and the group indication of isolation valves of containment provide information belonging to the inter-system level. Grouping individual status indicators can push the level of information upward because such a group presents emergent patterns of system malfunction, instead of individual component status.

Secondly, the characteristics of human tasks in the two types of MCRs are different. The board operators (BOs) (e.g., reactor operator, turbine operator, electric operator) in a CMCR have to observe the process parameters, compare the values with the corresponding set-points, and report the results to the shift supervisor (SS). The SS then integrates the results to assess the states of the sub-systems or the system, and to determine if inter-system safety functions are satisfied. In contrast, in an AMCR, the board operators' tasks tend to consist of identification rather than observation and comparison, because the operators directly obtain transformed high-level information from the advanced displays [8].

Table 1
Examples of information levels in NPPs.

Level	Examples
Component	Level/pressure/temperature indicator for each process parameter
Sub-system	Containment spray system (CS), reactor coolant system (RC), BISI, etc.
System	Primary system, auxiliary system, secondary system, turbine generator system, electric system
Inter-system	Critical safety functions such as the reactor coolant system inventory

For instance, in the Loss of Coolant Accident (LOCA) scenario, the board operators of a CMCR have to monitor various process parameters on several control boards to verify whether the conditions for LOCA entry are met. In an AMCR, operators can quickly grasp the overall situation by monitoring the high-level information on a visual display terminal (VDT), and can confirm the specified abnormal conditions on the basis of lower-level information. This level-by-level confirmation continues until the operator acquires a full characterization of plant conditions.

2.2. The need for a more inclusive perspective

Analysis of human–human communication alone cannot capture the effects discussed above of the presence in AMCRs of advanced information processing by a technical system. Therefore, we need a more inclusive framework that integrates human–human communication and the information processing by the system that produces the common basis for communication.

In general, communication is understood as information exchange between humans. Much research in the aviation industry has focused on communication, because communication errors are a major cause of air traffic incidents. Communication analyses in the aviation industry have mainly investigated the remote communication between air traffic controllers and pilots [12–14], and a few studies have examined the communication between the crew in cockpits. Although the results of this research have reduced aviation accidents, the research focus has been confined to human–human communication [15,16].

Another body of research has dealt with the interaction between humans and technical systems, and is characterized with the titles Human–Machine Interface (HMI), Human–System Interface (HSI), and Human–Computer Interaction (HCI). The main emphasis in this research has been the design of the human interface with the technical system, since the information presented by the technical system affects the cognitive processes of human users. As information technology advances, technical systems have become more intelligent and have more sophisticated information processing and presentation capabilities. The interaction between humans and technical systems can now be viewed as information exchange, explicit or implicit, i.e., as human–system communication.

The approaches of both lines of research are of limited use for the analysis of information exchange in large-scale dynamic systems such as nuclear power plants (NPPs) because they exclude crucial participants. Studies of human–human communication mainly analyze human conversation from social perspectives. The results of such analyses tend to characterize communication superficially without referring to mental models or the cognitive stages of workers and without considering the information processing capabilities of the technical system. On the other hand, most studies with an HMI perspective focus their attention on cognition at the individual level. Although it is well known that changes in the design of HMIs have brought about changes in the cognitive processes of individual users, very few studies have tried to investigate the effect of HMI design on communication at the group level [17].

Information provides an externally perceivable and shareable basis for communication between humans and between humans and technical systems. We do not address all human–system interface issues in this paper. However, understanding the path of information exchange between the system and humans appears to be essential, since the growing information processing capability of modern systems means that more of the information processing is computerized, which alters the communication between humans. This rationale leads to the proposed analytic