Safety Science 79 (2015) 286–297

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

A human-system interface risk assessment method based on mental models

Mohsen Naderpour *, Jie Lu, Guangquan Zhang

Decision Systems and e-Service Intelligence Laboratory, Centre for Quantum Computation & Intelligent Systems (QCIS), Faculty of Engineering and Information Technology, University of Technology Sydney (UTS), PO Box 123, Broadway, NSW 2007, Australia

ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 23 June 2015
Accepted 1 July 2015
Available online 10 July 2015

Keywords:
Risk assessment
Situation awareness
Situation awareness measurement
Human-system interfaces
Mental models

ABSTRACT

In many safety–critical systems, it is necessary to maintain operators' situation awareness at a high level to ensure the safety of operations. Today, in many such systems, operators have to rely on the principles and design of human-system interfaces (HSIs) to observe and comprehend the overwhelming amount of process data. Thus, poor HSIs may cause serious consequences, such as occupational accidents and diseases including stress, and they have therefore been considered an emerging risk. Despite the importance of this, very few methods have as yet been developed to assess the risk of HSIs. This paper presents a new risk assessment method that relies upon operators' mental models, human reliability analysis (HRA) event tree, and the situation awareness global assessment technique (SAGAT) to produce a risk profile for the intended HSI. In the proposed method, the operator's understanding (i.e. mental models) about possible abnormal situations in the intended plant is modeled on the basis of the capabilities of Bayesian networks. The situation models are combined with the HRA event tree, which paves the way for the incorporation of operator responses in the assessment method. Probe questions in line with the SAGAT through simulated scenarios in a virtual environment are then administrated to gather operator responses. Finally, the proposed method determines a risk level for the HSI by assigning the operator responses to the developed situational networks. The performance of the proposed method is investigated through a case study at a chemical plant.

1. Introduction

Following several high impact disasters such as those at Three Mile Island, Bhopal and Chernobyl, many high-hazard industries have focused on different contributing factors to reduce their accident rates as much as possible. In most industrial accidents, there is a chain of organizational conditions and human errors which show that 70–80% of such accidents are attributable to human-factor causes (Isaac et al., 2002; Sneddon et al., 2006). Among those causes, the ability of operators to maintain an adequate understanding of their worksite situations is a critical factor in preventing accidents. This cognitive ability is referred to as situation awareness (SAW); it indicates a high level of awareness of task and environmental conditions, as well as the ability to predict how these conditions may change in the near future to aid understanding of how situations will develop (Nazir et al., 2012, 2014b). To date, several SAW models such as Taylor (1990), Endsley (1995b), Adams et al. (1995), and Bedny and Meister (1999), have been developed; however, Endsley's model has undoubtedly received the most attention. This information processing-based model describes SAW as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". It introduces SAW as a product that has three levels: Level 1, the perception of relevant elements in the task environment; Level 2, the comprehension of the elements with regard to the goals; and Level 3, the projection of the state of those elements in the near future (Endsley, 1995b).

In many safety–critical systems today, advanced control rooms are equipped with many automated systems; however operators are still responsible for accident diagnosis and mitigation, thus information acquisition and decision making are emphasized more than manual manipulation. Human-system interfaces (HSIs) should therefore support operators by helping them to understand situations and act more effectively and less ambiguously. Poor HSI can have serious consequences, such as occupational accidents and diseases including stress, therefore HSI has recently been considered an emerging risk which may jeopardize safety (Flaspoler

* Corresponding author. Tel.: +61 2 95142644.
E-mail addresses: Mohsen.Naderpour@uts.edu.au (M. Naderpour), Jie.Lu@uts.edu.au (J. Lu), Guangquan.Zhang@uts.edu.au (G. Zhang).

http://dx.doi.org/10.1016/j.ssci.2015.07.001
0925-7535/

et al., 2009; Jovanovic and Balos, 2012). To design an adequate HSI, the specific properties and qualities of human factors as well as the working environment must be taken into account, but very few methods and tools have as yet been developed to assess this kind of risk in the design of HSIs, despite its importance. Fuchs-Frothnhofen et al. (1996) proposed a methodology to incorporate users' mental models in a HSI for a CNC system. Carvalho et al. (2008) suggested several principles based on human factors to improve an interface screen, alarm system, and procedure guidelines in a nuclear power plant simulator. Ha and Seong (2009) proposed a difficulty evaluation method in information search, based on two measures: Fixation-to-importance ratio and selective attention effectiveness. Lee et al. (2013) recently developed a computational situation assessment model to design HSIs in nuclear power plants based on SAW.

This paper argues that a range of methods and techniques are required for evaluating the safety of HSIs from the human factor perspective. It may be argued that human error is best examined from a cognitive perspective, as traditional reliability engineering techniques do not appear to fit well with human factor concerns. Therefore, it may be more appropriate to quantify safety from a human factor perspective in terms of the level of SAW acquired through the interface. In this sense, the paper considers operators' behavior when they are confronted with abnormal situations in a safety–critical environment. To achieve this, the operators' mental models with regard to possible abnormal situations in the intended plant are first modeled by exploiting the capabilities of Bayesian networks (BNs). Secondly, the aspects of the situation that are important for operators' SAW are determined using a cognitive task analysis called goal-directed task analysis (GDTA) methodology. Thirdly, online probe questions based on identified SAW requirements and in line with the situation awareness global assessment technique (SAGAT) are administrated in a simulation environment where operators' responses are collected and assigned to developed BN-based situational networks as evidence to form the assessment result.

The paper is organized as follows. Section 2 presents the operators' cognitive activities. Section 3 describes the operators' mental models. Measuring SAW is explained in Section 4. The HSI risk assessment method is presented in Section 5. The performance of the proposed method is investigated in Section 6 in which a residue treater unit at a chemical plant is used for demonstration. The conclusion and future work are outlined in Section 7.

2. Operators' cognitive activities

Large-scale technological systems usually contain multilevel control loops and interconnections which need to be monitored and supervised for normal operations. Once the system becomes unstable, the conditions are referred to as an abnormal situation, which can lead to near misses and possible accidents with both economic and human loss. In the last two decades, technological systems have experienced a significant increase in multidimensional automation that has significantly increased the complexity and sensitivity of the role of operators and their teams. However, the operators lack the ability to intervene or tackle abnormal situations as such systems are usually designed for routine operating conditions (Nazir et al., 2013, 2014a). Therefore, any attempt to develop operator support systems should consider both normal and abnormal situations.

Generally, the cognitive tasks that operators perform to carry out their roles and responsibilities include monitoring and detection, situation assessment, response planning, and response implementation (O'Hara and Persensky, 2011), as illustrated in Fig. 1. Any breakdown in these generic tasks can lead to human error. Therefore, a balanced automated system that avoids an excessive workload for its operators and keeps them in the loop of decision-making, taking action, and updating related information will benefit the intended industry. The activities involved in extracting information from the environment are referred to as monitoring and detection. In current systems, this task is highly supported through various heterogeneous sensors and appropriate signal-processing methods that are used to extract as much information as possible about the dynamic environment. Good monitoring results in operators' achieving perception or SAW level 1. Situation assessment is the evaluation of current conditions to determine whether they are acceptable, or to discover the underlying causes of abnormalities. Situation assessment which underlies the achievement of SAW is therefore critical to taking appropriate human action. The HSI must thus provide additional support for assessing the situation besides providing alarms and displays that are used to obtain information to support situation assessment. This development corresponds to SAW levels 2 and 3, which enable support operators to infer real situations and to project their status in the near future. Response planning refers to deciding upon a course of action to address the current situation. In general, response planning involves operators using their situation model to identify goal states and the transformations required to achieve them. Response implementation is performing the actions specified by response planning. These actions include selecting a control, providing control input, and monitoring the system and process response (O'Hara and Persensky, 2011).

The human reliability analysis (HRA) event tree is a technique that shows that the final operation result is correct if the components of all four cognitive tasks have been carried out correctly. Fig. 2, a_c and a_i indicates the probability of an operator reading an indicator correctly or incorrectly. As can be seen, the basic event tree does not include a decision support system. If a decision support system is used in any step, new branches are added to the basic event tree. For instance, f_c and f_i refer to the probability that the support system will generate correct or incorrect results. q represents the probability that the operator will recognize incorrect diagnosis results produced by the support system, while r indicates the recovery probability that an operator who has assessed the situation incorrectly will make a decision change based on correct results delivered by the support system (Lee et al., 2008). As in this paper, a simulated environment is used to show the performance of the HSI risk assessment method, the first three layers – monitoring, situation assessment, and response planning – are just considered.

3. Operators' mental models

The concept of mental models has a very long tradition in applied cognition. Mental models are mechanisms that enable humans to generate descriptions of system purpose and explanations of system functioning (Endsley, 2000b). Mental models embody stored long-term knowledge about systems that can be called upon to interact with the relevant system when needed. These internally developed models aid in efficiently directing limited attention. They provide a way to integrate information without overloading working memory. The use of mental models to achieve SAW is believed to be dependent on the individual's ability to pattern match critical cues in the environment with elements in their mental model, and being able to incorporate the use of these models into SAW can provide the operator with quick retrieval of actions from memory (Pridmore, 2007).

Mental models have often been used in studies trying to model human control of various processes. Rouse and Morris (1986) define mental models as "mechanisms whereby humans are able