Decision Support Systems 59 (2014) 325–340

Contents lists available at ScienceDirect

Decision Support Systems

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

An intelligent situation awareness support system for safety-critical environments

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ARTICLE INFO

Article history:
Received 23 April 2013
Received in revised form 27 November 2013
Accepted 9 January 2014
Available online 17 January 2014

Keywords:
Decision support systems
Cognition-driven decision support
Situation awareness
Situation assessment
Risk assessment
Bayesian networks

ABSTRACT

Operators handling abnormal situations in safety-critical environments need to be supported from a cognitive perspective to reduce their workload, stress, and consequent error rate. Of the various cognitive activities, a correct understanding of the situation, i.e. situation awareness (SA), is a crucial factor in improving performance and reducing error. However, existing system safety researches focus mainly on technical issues and often neglect SA. This study presents an innovative cognition-driven decision support system called the situation awareness support system (SASS) to manage abnormal situations in safety-critical environments in which the effect of situational complexity on human decision-makers is a concern. To achieve this objective, a situational network modeling process and a situation assessment model that exploits the specific capabilities of dynamic Bayesian networks and risk indicators are first proposed. The SASS is then developed and consists of four major elements: 1) a situation data collection component that provides the current state of the observable variables based on online conditions and monitoring systems, 2) a situation assessment component based on dynamic Bayesian networks (DBN) to model the hazardous situations in a situational network and a fuzzy risk estimation method to generate the assessment result, 3) a situation recovery component that provides a basis for decision-making to reduce the risk level of situations to an acceptable level, and 4) a human-computer interface. The SASS is partially evaluated by a sensitivity analysis, which is carried out to validate DBN-based situational networks, and SA measurements are suggested for a full evaluation of the proposed system. The performance of the SASS is demonstrated by a case taken from US Chemical Safety Board reports, and the results demonstrate that the SASS provides a useful graphical, mathematically consistent system for dealing with incomplete and uncertain information to help operators maintain the risk of dynamic situations at an acceptable level.

1. Introduction

Safety-critical environments are those domains in which hardware failure or poor or late decision-making by operators could result in loss of life, significant property damage, or environmental pollution. In many safety-critical environments today, the role of the operator shifts from a person who controls a process manually to a supervisor or decision-maker, and includes extensive cognitive tasks [15] including information gathering, planning, decision-making, demonstrating that the facility is fit for its intended purpose, and ensuring that the risks associated with its operation are sufficiently low [34]. In abnormal situations, a well-trained operator should comprehend a malfunction in real time by analyzing alarms, assessing values, and recognizing unusual trends associated with multiple instruments. When confronted with a complex abnormal situation, many alarms from different systems may sound at the same time, making it difficult for operators to judge within a short period of time which situation should be given priority. To return operational units to normal conditions, operators must respond quickly and make rapid decisions, but the mental workload of operators under these circumstances rises sharply, and a mental workload that is too high may increase the rate of error [17]. Paradoxically, several researches show that the focus of most human-system studies is on the technical elements, and human factors are often neglected [39]. This is due to well understood hardware reliability techniques, whereas the handling of human factors, by contrast, is difficult. These problems highlight the urgent need to discover cognitive decision support systems to manage abnormal situations that will lower operator workload and stress and consequently reduce the rate of errors made by operators.

Decision support systems (DSSs) are envisioned as "executive mind-support systems" that are expected to support decision-making from a human cognition perspective [4]. Over the years, some types of DSS, such as model-driven and data-driven DSSs, have achieved increased popularity in various domains. Model-driven DSSs emphasize the creation and manipulation of statistical, financial, optimization, or simulation models that require decision makers to specify model parameters according to their decision problems. The functionality of data-driven DSSs results from access to, and manipulation of, a large database of structured data, and their outputs are based on perceiving and comprehending the integrated information [41]. Unlike model-driven

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http://dx.doi.org/10.1016/j.dss.2014.01.004

and data-driven DSSs, cognitive DSSs have not been researched, albeit they have long been recognized as being worthy of consideration [4]. Just as a cognitive process refers to an act of human information processing, so a cognition-driven decision support system refers to assisting operators in their decision-making from a human cognition perspective, using attributes such as sensing, comprehending and projecting [39]. Of these cognitive aspects, an operator's situation awareness (SA) is considered to be the most important prerequisite for decision-making. Situation awareness comprises the perception of elements in the environment, the understanding of their meaning, and the projection of the status of that environment in the near future [10]. Situation awareness is likely to be at the root of many accidents in safety-critical environments where multiple goals must be pursued simultaneously, multiple tasks require the operator's attention, operator performance is under high time stress, and negative consequences associated with poor performance are anticipated [22]. To give an example: On 14 June 2006 in an explosion at a chemical plant, one person was killed and two employees were injured when the operator could not maintain accurate SA and the vapor overflowed from the tank [5]. This case will be investigated in this paper as an example of poor operator SA which led to a severe accident.

Based on these issues, the main objective of this study is to develop a cognition-driven DSS, called the situation awareness support system (SASS), with the purpose of developing a comprehensive and practical operator support system for use in abnormal situations. The proposed SASS consists of four major components: 1) situation data collection (e.g. observable variables such as sensors), 2) situation assessment, which includes a dynamic Bayesian network-based situational network to model situations of interest and a risk estimation method to generate the assessment result, 3) situation recovery, and 4) a human-computer interface. The proposed system has the following advantages:

1) In most human-system studies, safety has been considered from a technical perspective. Only hazards that arise through hardware failure have been considered, despite the fact that human failure is a more common factor in safety-critical systems. To develop the system in this study, two important aspects, namely addressing hazards that result from hardware failure and reducing human error through decision–making, have been considered. A situation modeling process based on hardware and human failure is proposed to model hazardous situations, and a situation assessment model is developed to support operators to achieve and maintain SA, and to make correct decisions.
2) The proposed SASS does not control the manner of implementing actions and allows individual discretion in the choice of human action for the specific context. It has been shown that increased automation does not necessarily result in improved capability, because approaches that focus solely on automated features disconnect the operator from the system and alienate them from the production process [2]. Therefore, the SASS keeps operators in the loop of decision-making and action-taking.
3) The proposed SASS assists operators to avoid unforeseen risks in the operation system and to determine appropriate ways to eliminate or control hazards until their risk level falls As Low as Reasonably Practicable (ALARP), thus ensuring that the proposed system conforms to ALARP.
4) The proposed SASS includes a situation assessment component that uses dynamic Bayesian networks, which has certain advantages over other situation assessment methods that use artificial intelligence tools such as expert systems [36] and neural networks [37]. First, it includes nodes and directed arcs to express the knowledge, and new information can be transmitted by directed arcs between nodes. Second, knowledge in the component can be updated, whereas updating knowledge in expert systems is difficult. Third, it already has expert knowledge encoded in its construction, while neural networks must learn knowledge via datasets, assuming training data are available. Lastly, the cumulative effect of situations based on new evidence is very suitable for SA continuity, whereas this feature does not exist in other artificial intelligence tools [46].

This study makes three important contributions. First, it proposes a situational network modeling process which is used to model abnormal situations in one or more networks. Second, it presents a situation assessment model that exploits the specific capabilities of dynamic Bayesian networks and fuzzy risk analysis. The proposed situation assessment model can be applied to other related domains if the risk indicators for any measurement are appropriate. Third, it develops, for the first time, a SASS for managing abnormal situations in safety-critical environments in which the degree of automation and complexity continues to increase and the number of operators decreases, and where each operator must be able to comprehend and respond to a growing amount of risky status and alert information.

The paper is organized as follows. Section 2 presents the background of this study. A literature review of SA and related areas is given in Section 3. The methodology for this study is provided in Section 4, and the requirements, model, and components of the SASS are explained in Section 5. A case from US Chemical Safety Board investigation reports (www.csb.gov) is presented in Section 6 to demonstrate the performance of the SASS. Section 7 compares our model with an existing situation assessment model and discusses the limitations of this study. The conclusion and future work are summarized in Section 8.

2. Background

This section describes the background to this study, including situation awareness, Bayesian network theory and the preliminary concepts of fuzzy sets and fuzzy logic systems.

2.1. Situation awareness

A situation is a set of circumstances in which a number of objects may have relationships with one another and the environment. Situation awareness can be described 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" [10]. This SA model follows an information processing chain from perception, through comprehension, to projection. Fig. 1 enables a clear understanding of the definition of both 'situation' and 'SA'. It shows four planes, each of which refers to a different level of abstraction. The bottom layer shows the World, which includes physical or conceptual things, or both. To the right of the World plane, a human head depicts the fact that SA is a state of knowledge which takes place in the human brain. The human is unable to observe all aspects of the World, and therefore has to obtain inputs from the computer for better appreciation (i.e. the arrow between the computer and the human head). The dots on the next layer (i.e. Perception) represent the objects from the World that are observed through sensors and represented in computer memory. The arrow pointing from the World plane to the radar icon represents the sensory process, which then feeds the computer. The emphasis in situation definition is on relationships which are described from the point of view of a thing (i.e. focal object), and how other things in the surroundings are related to it. This plane represents Comprehension. The top layer illustrates the Projection, and this layer is defined as the ability to anticipate future events and their implications [28].

2.2. Bayesian networks

A Bayesian network (BN) is a mathematical graphical representation method that provides an opportunity to model a causal process with uncertainty. Each node represents a variable and the arcs show direct probabilistic relations between the connected nodes. Dynamic BNs