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A cognitive reliability model research for complex digital human-computer interface of industrial system

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ABSTRACT

Nowadays, traditional human–machine interface has been converted into digital human–computer interface in most industrial control rooms, then, cognitive process and reliability are also bound to be different from traditional human–machine interface. Aiming at the situation, the authors in this paper propose a cognitive reliability model with influencing factors based on Bayesian network. Taking a nuclear power plant (Npp) as research background, taking simulative experiment as study way, parameter values in cognitive reliability mathematical model are obtained by analyzing much experimental data. The proposed model is reasonable, accurate, sensitive and convergent by analyzing experiment data. Cognitive error probabilities of some tasks regarding a hot transmission system (HTS) leak accident in a Npp are obtained according to the proposed model and simulative experiments. The model provides a simple and feasible approach to analyze cognitive reliability of operating process in digital human–computer interface.

1. Introduction

Currently, digital human-computer interface in most control rooms has brought operators great challenge. Once an accident in digital system occurs, the aftermath could be very serious, For instance (Carvalho et al., 2006) the accident at Three Mile Island (TMI) in 1979, the nuclear accident at Chernobyl in 1986. Although the reliability regarding hardware and software system has been improved with technique progress, human beings has many uncertain features, then the accidents caused by human error are very easily to occur. Just data showed that 60–90% accidents are caused by human error.

On the one hand, digital human-computer interface has many advantages, for instance (Lewis and Persensky, 2002): (1) there are navigation systems that can instruct operators to get into and recover graphic interfaces; (2) it has powerful query function; (3) it has many shortcut ways that can easily manage interface tasks. On the other hand, it has brought operators new challenge, which mainly reflects the change of cognitive behavior. Thus, traditional models are not appropriate for cognitive reliability evaluation of digital human-computer interface. Further, traditional reliability theories are based on binary logic, such as, Fault Tree Analysis (Weber and Jouffe, 2006) (FTA) generally viewed object as only two states (absolute failure or absolute reliability), and neglected the degree of systematic performance influenced by mutual factors and failure systematic components. In fact, system and each component have many states. Then, reliability model built by traditional way differs from realistic situation, and that cannot meet current systematic performance analysis. Many scholars proposed some methods for multi-states systematic reliability and dynamics (Kohda and Cui, 2007; Barrientos and Vargas, 1998; Labatut et al., 2004; Chevrolat et al., 1998), but the methods have some limitations to analyze the multiple states of human. Recently, Bayesian method has successfully been applied to fault diagnosis, data mining, artificial intelligence and reliability analysis research fields. Bayesian Networks can easily show randomness, uncertainty and relevance between variables. Taking a nuclear power plant as research background, the authors in this paper propose a cognitive reliability model for digital human-computer interface based on Bayesian networks.

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2. Related works

Cognitive reliability studies primarily focus on human psychological inner mechanism, and that involve philosophy, psychological, information science, neurology, linguistics, computer science, evolutionary biology and animal behavioral biology, etc. Baron et al. (1980) Proposed process-oriented crew model that consisted of three members by simulating crew behavior. The model mainly studied crew communication process and performance influencing factors. In 1982, OAT method was proposed (Hall et al., 1982), the main advantage of this method made use of time relationship and error probability analysis of action diagnosis. Seaver and Stillwell (1983) proposed PC method, this method had two characteristics: (1) obtained results were from expert judgment; (2) it is very difficult to analyze the errors of complex tasks. Hannaman et al. (1984) presented HCR (Human Cognitive Reliability) model that was one of models to quantitatively analyze human reliability. It divided operator behavior into three types referred as skill, rule and knowledge, respectively, and that offered a tool to analyze human reliability for man-machine interface. As perception, analysis and decision-making usually are made up of human various abilities, the model is very difficult to classify the skill, rule and knowledge. On the other hand, the model only pondered permitting and executing time, it neglected specific task features and absolute time influence on human error probability. In the same year, a SLIM (Success Likelihood Index Method) was proposed (Embrey, 1984). The method was based on expert judgment, so it had some limitations. Woods et al. (1987) studied cognitive environment by artificial intelligence and operator actions in nuclear power plant control room. Cacciabue et al. (1992) proposed a cognitive simulation model by artificial intelligence program. The model mainly researched the operating action of nuclear power plants in a special circumstance. To evaluate human reliability, Philips et al. (1995) proposed STAHR method. This method had two prominent characteristics: (1) to a great extent it mainly relied on subjectivity and psychological conditions; (2) it had strong sensitivity. Straeter (1997) described the accident analysis and cognitive reliability method (Cognition Assessment Human Research, CAHR) in his PhD thesis. The method was based on the accidents occurring in nuclear power plants in German, and that could quantitatively analyze human error probability. Hollnagel (1998) proposed a cognitive reliability and error analysis method (CREAM). CREAM was a developing HRA method based on cognitive and context control model. It used some basic research results completed in 1993 by himself. Martin et al. (1999) put forward an OAA model that could communicate with each agent module by regression framework. The model mainly emphasized on psychological situation of a team. Blom et al. (2000) proposed ATM operational risk assessment based on Scenario and Monte carlo event hazards. Later, he defined the hazard of relevant operation and collected the impact factors. The model was based on human cognitive reliability analysis at different cognitive levels in correlation context, and that combined with impact risk model. Goldberg (2001) presented a computational model, this model differed from general statistical and mathematical models, because the model contained the influencing factors of human behavior. It was obtained by simulating some behavior characteristics via computer program. Shu et al. (2002) described team behavior model. The model consisted of four parts: the task execution model, the initial event model, posteriori event exploitative model and team model of human-machine interface. The model mainly focused on team cognitive process for learning and recognizing representation. Khrennikov (2009) came up with a quantitative cognitive model about decision-making and information process. The model mainly studied digital measurement and decision-making quantitative analysis based on psychological context. Fan et al. (2010) proposed a HMM-based model for members of human-agent teams. The model have a three-layer structure, and can be used in instruct the selection of HMM-based cognitive load models in human-centered multi-agent systems. Murray and Johnson (2013) expressed a question of whether the bi-factor or higher-order model is the more appropriate model for human cognitive ability structure. The results suggest that decisions as to which model to adopt either as a substantive description of human cognitive ability structure or as a measurement model in empirical analyses should not depend on which is better fitting. By contrasting the CDA/CDM framework against existing assessment frameworks, which are typically based on item response theory or classical test theory, Torre shown that CDAs used in the CDM context may provide valuable diagnostic information (2014). A computational model is proposed based on dual system theory and cognitive control perspective of decision-making (Zendehrouh, 2015). The basic finding is that the brain implements a dual controller, while an accompanying monitoring system perceives some kinds of conflict. A computational model to calculate a user's desirability based on personality in e-learning environments was proposed (Fatahi and Moradi, 2016). The model can predict the desirability of the events based on the user's personality and his/her goals, and has high accuracy to formulate the relationship between personality and emotions.

3. Proposed cognitive reliability model for complex digital human-computer interface of industrial system

Compared with traditional human-machine interface, human cognitive behavior in digital human-computer interaction is greatly different, for example: (1) in addition to deal with traditional components, operators need to observe and analyze a huge number of parameters, perform emergency procedures, plan secondary tasks, search navigation information, etc.; (2) the parameters and procedures are dynamic changes; (3) the positions to display information and procedures on screens are not fixed. Then traditional cognitive model cannot be quite qualified with the human reliability evaluation of digital human-computer interface. Aiming at the situation, present section discusses a mathematical model for cognitive process of digital human-computer interface.

3.1. Influencing factors

In cognitive research field, Edwards (1987) proposed SHELL model. Later, this model was improved by Hawkins (1987). Hawkins considered the software equipment, factory condition and the PSFS (Performance Shaping Factors, PSFs). Similar, the proposed model in this paper includes several PSFs that are mainly used to calculate cognition reliability.

Nowadays, there are some achievements on PSFs of human-machine system. Such as, Chang and Mosleh (2007a, 2007b) in a series of papers proposed the IDAC cognitive model including many external and inner factors. Based on SHELL and IDAC models, literature surveys and field investigations, the authors in this study consider four main influencing factors of cognitive process, as listed in Table 1.

Table 1
Influencing factors in cognitive process.

Influencing factor types	Influencing factors (f)	Symbol	Level		Symbol
Inner influencing factors (Kecklund and Svenson, 1997)	Experience	f1	Excellent	L1	f11
			General	L2	f12
			Beginner	L3	f13
Physiological factor (Swain and Guttmann, 1983)	Psychological stress	f2	Relaxed	L1	f21
			General	L2	f22
			Heavy	L3	f23
External influencing factors (Malone et al., 1979)	Task complexity	f3	Low	L1	f31
			Average	L2	f32
			High	L3	f33
	Human-computer interface	f4	Good	L1	f41
			General	L2	f42
			Poor	L3	f43