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Quantifying situation awareness of control room operators using eye-gaze behavior

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ABSTRACT

In an attempt to improve process safety, today's plants deploy sophisticated automation and control strategies. Despite these, accidents continue to occur. Statistics indicate that human error is the predominant contributor to accidents today. Traditionally, human error is only considered during process hazard analysis. However, this discounts the role of operators in abnormal situation management. Recently, with the goal to develop proactive strategies to prevent human error, we utilized eye tracking to understand the situation awareness of control room operators. Our previous studies reveal the existence of specific eye gaze patterns that reveal operators' cognitive processes. This paper further develops this cognitive engineering based approach and proposes novel quantitative measures of operators' situation awareness. The proposed measures are based on eye gaze dynamics and have been evaluated using experimental studies. Results demonstrate that the proposed measures reliably identify the situation awareness of the participants during various phases of abnormal situation management.

1. Introduction

Process safety is a major concern in the chemical and allied industries. Accidents large and small torment plants regularly; their annual cost is estimated to be in the millions, even for medium-sized facilities (Mannan, 2004). Over the last three decades, numerous interventions have been made by governments and industries around the world to improve process safety. Despite these, there is no significant abatement in accident occurrence – a recent survey (Marsh, 2014) reported that 25% of the accidents that led to largest losses in the hydrocarbon industry over a period of 40 years happened in the last 5 years from 2009. There has however been a notable change over time in the key contributory causes of accidents. In the early days, inadequate system reliability and insufficient understanding of process phenomena were the key reasons leading to accidents. More recently, process plants widely use highly reliable systems with sophisticated automation and control strategies. Statistics show that the predominant root cause of accidents in the process industry now is human error (Mannan, 2004). An analysis (Sepeda, 2006) of over 80 incidents revealed that human-related factors contribute significantly to incidents. Symptoms of human factors related deficits in a plant include stress (Rasmussen and Laumman, 2014) on operators and shift supervisors, which in turn translates to slips, lapses, mistakes, or violations and cause equipment outage, plant shutdown and various production accidents (Kidam et al., 2010). This highlights the need to develop a deeper understanding of human error in the process industry and new techniques to prevent them (Gordon and Rachael, 1998).

Traditionally, human errors have been accounted for during risk assessment of the process design. Various types of human failures and their expected probabilities of occurrence were incorporated in Process Hazard Analysis (Munger et al., 1962; Swain, 1990) i.e., human error was viewed as the initiating event of incidents using likelihood approaches, similar to the way that a piece of hardware is expected to fail at some frequency. The role of the human in any complex system such as a process plant has evolved over the last three decades from being predominantly manual (physically 'doing' a task) to being predominantly cognitive (requiring 'thinking'). The nature of human errors that affect the system's safety has therefore evolved, as exemplified by the Three Mile Island Nuclear Plant accident (Le Bot, 2004). Rasmussen suggested a model of

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behavioral shaping mechanisms to model failures in human performance using cognitive science concepts (Rasmussen, 1997). Motivated by these, effort has been focused on designing ergonomic control rooms or user-centered design of human-machine interfaces (Cochran and Bullemer (1996)). A number of risk assessment techniques have also been developed (Chang and Mosleh, 2007; Pate-Cornell et al., 1996). There has however been little effort to understand the cognitive state of operators in real-time during process operations and its impact on process safety (Kodappully et al., 2016; Sharma et al., 2016).

Recent advancements in the biomedical arena has led to various tools such as Electroencephalography (EEG), functional Near Infrared imaging (fNIR), Galvanic Skin Response (GSR) and eye tracking which could be used to understand the cognitive behavior of humans. Among these, our research has focused on eye tracking since it is non-invasive and can be relatively easily deployed in a control room (Kodappully et al., 2016; Sharma et al., 2016). Our previous studies demonstrated qualitatively that during process operations, the control room operator's gaze on the Human-Machine Interface can reveal the extent of his situation awareness and thus his ability to handle any disturbance successfully before it escalates into an accident. The current work aims to develop *quantitative* measures of eye gaze behavior that can supplement the qualitative understanding developed in our prior work. The rest of this article is organized as follows. Section 2 presents an overview of eye tracking and reviews the literature on various attempts to quantify the gaze behavior of operators in various domains. The proposed entropy measures used in this work for quantification of eye gaze behavior are discussed in Section 3. Section 4 reports three potential applications of the proposed entropies as well as detailed results from large-scale studies.

2. Literature review

In a process plant, control room operators typically interact with the process through the Human Machine Interface (HMI) of the Distributed Control System (DCS). The role of the operator is to monitor and control the process so that disturbances do not propagate and lead to an abnormal situation that may escalate to an accident (Pariyani et al., 2010). The performance of the control room operator is therefore critical to process safety.

The potential for eye tracking as a means to infer operators' cognitive processes and assess situation awareness was highlighted by Ujita (1992). Eye tracking can be used to prevent or reduce human errors on the part of the control room operator. In an eye tracker, a light source is used to illuminate the eyes of the subject (viz, the control room operator) and a camera used to capture images of the eyes. The image captured is then used to locate the reflection of the light source on the cornea and in the pupil (Holmqvist et al., 2011). The reflected light is captured by a camera and the image processed using proprietary algorithms to calculate an eye gaze vector which provides the location (2-dimensional point) of the operator's gaze on the HMI screen. It also provides a measure of the pupil diameter. Both the gaze and pupil diameter can be measured at high frequency (e.g. 200 Hz) and thus offer fine-grained insight into the subject's eye activity which can be analyzed to obtain cognitive insights.

The eye is characterized by both voluntary and involuntary movement. According to the eye-mind hypothesis, eye movements offer a dynamic trace of a person's attention, mental processing, and cognitive states. Research has shown that the movement of the eye contains specific events (Duchowski, 2007; Majaranta and Raiha, 2002). Typically, eye movement is segmented into two distinct patterns, called fixations and saccades. When reading, the eye temporarily stops at a word and remains still for a period of time. This pause in eye movement is called a fixation and is necessary to stabilize the image of the word on the retina. Fixations typically last between tens of milliseconds up to several seconds. The eye also rapidly moves from word to word during reading, i.e., from one fixation to another. Such rapid movement is called a saccade. Various measures can be derived from fixation and saccades to help understand the cognitive behavior. Some widely used ones include dwell duration – duration of all visits within an Area of Interest (AOI); saccadic velocity – the first derivative of position data with respect to time; and AOI order – the sequential order of movement between the AOIs. These measures have recently been used in various safety critical fields such as aviation, healthcare, and driving to understand the cognitive actions of human subjects.

In aviation, fixation measures computed from eye tracking data has been used to monitor and assess the performance of pilots (Kilingaru et al., 2013; Schulz et al., 2011; Hasse and Grasshoff, 2012). As one example, Kilingaru et al. (2013) used dwell duration (fixation on AOI) and gaze transitions to understand the behavior of expert and novice pilots. Based on the dwell duration, the cognitive state of the operator is categorized into three states: (i) attention focusing with continuous dwell on specific instruments, (ii) attention blurring with short dwells, and (iii) misplaced attention with extended dwell outside the instrument panel. Eye gaze data has also been used to understand the usability of newly developed electronic 3-D maps used in the cockpit (Ottati et al., 1999). One important observation from these studies was that experienced pilots had significantly long dwell durations, while novices had less navigational dwells and performed poorly. Another work by Li et al. (2012) evaluated the pilot's situation awareness using dwell duration analysis. Several other works have been conducted in the field of aviation to understand the mental workload, situation awareness, and expertise level of pilots (Wanyan et al., 2014; Dehais et al., 2008; Ellis, 2009).

In healthcare, dwell duration and fixation measures have been used to identify novice and expert surgeons using a virtual laparoscopic simulation environment (Law et al., 2004; Wilson et al., 2013; Tien et al., 2010; Eivazi et al., 2012). Studies revealed that novice surgeons focused on the surgical display while failing to notice the patient's vital signs even when the heart rate audibly changed during the procedure. A study by Tourassi et al. (2013) addressed the diagnostic problems during interpretation of medical images. A series of experiments were performed for mass detection in mammograms obtained during breast cancer screening. The radiologist's gaze pattern was monitored and gaze characteristics were linked to the image content. This eye gaze analysis helped to predict the diagnosis made by the radiologist. Several works have been performed to qualitatively understand the cognitive behavior of surgeons and radiologists using eye gaze studies (Jiang et al., 2010; Burgert et al., 2007; Chetwood et al., 2012).

In the field of driving, dwell duration analysis has been conducted to understand the performance of expert and first-time motorbike riders. It was observed that, compared to experts, first-time riders (before training) had majority of their focus on irrelevant areas below and above the center of the road. However, after training, their fixation pattern matched that of experts with large duration on the road sides (Pradhan et al., 2005). Apart from understanding the expertise level, several studies based on eye gaze analysis have been conducted to analyze the situation awareness and mental work of drivers (Recarte and Nunes, 2000; Gilland, 2008). Experimental studies were also conducted to identify markers of driver fatigue (Di Stasi et al., 2012). These studies revealed that drivers suffering from fatigue had a significant decrease in peak saccadic velocity (highest velocity achieved during saccades) along with an increase in saccadic duration (time taken to complete a saccade). Eye tracking has also been used for evaluating operator