Situation Awareness-Oriented Alarm Visualizations: A next Step in HSC Environments

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Abstract: Due to their effective capability to fix the attention of control room operators to such conditions that require some kind of response, alarm visualizations have become key control artifacts in Human Supervisory Control environments. Nevertheless, the increasing complexity and interconnectivity of controlled processes highlights the necessity of new control artifacts that support both identification and diagnosis tasks. In this line of work, this paper posits the need of redesigning alarm visualizations in order to assist not only the real-time detection of failures but also the achievement of Situation Awareness by control room operators. Based on dynamic interaction and exploration capabilities, this new design perspective for alarm visualizations may improve the operator's ability to diagnose the causes of abnormal situations.

1 INTRODUCTION

Human Supervisory Control (HSC) is defined as "the process by which a human operator intermittently interacts with a computer, receiving feedback from and providing commands to a controlled process or task environment" (Sheridan, 1992, p. 1). Due to their capability to assist control room operators, alarm visualizations have been characterized as key control artifacts in HSC environments (Sheridan, 1992; Endsley et al., 2003; Ivergard and Hunt, 2009). Alarm visualizations refer to "the method(s) by which alarm coding and messages are presented to control room operators" (ISA, 2009, p. 50).

The primary objective of alarm visualization is to warn the operator about a condition that develops when the controlled process significantly deviates from the normal acceptable mode of operation (see Fig.1). However, effective alarm systems must be conceived not only to support the identification of failures but also to assist the diagnosis of the situation (Niwa and Hollnagel, 2001); understanding diagnosis as the act or process of deciding the nature of the operating condition by examination (Rasmussen, 1993). Accordingly, the next design challenge of alarm visualization should be to assist this thinking process.

The analyses of recent problems in HSC environments shows that the ability of control room operators for acquiring Situation Awareness (SA) is a major factor in failures propagation (Endsley et al., 2003; Greitzer et al., 2008). With increasing complexity and interconnectivity of the controlled processes, the scope and complexity of HSC continues to grow, in particular, the amounts and typologies of information that control room operators must process in quasi-real time (Greitzer et al., 2008), hampering the achievement of SA.

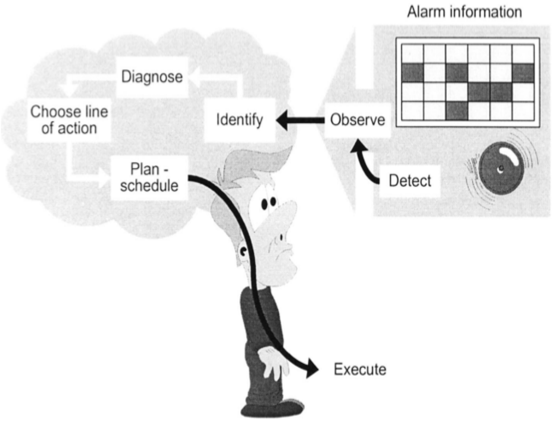

Figure 1: Alarm processing paradigm according to the primary purpose of an alarm system (Niwa and Hollnagel, 2001).

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This paper posits the need of redesigning alarm visualizations in order to assist not only the real-time detection of failures but also the achievement of SA by control room operators. Based on dynamic interaction and exploration capabilities, such SA-oriented alarm visualization may overcome human information processing limitations and, therefore, improve the ability of control room operators to diagnose the causes of abnormal situations.

This position paper first gives an overview of the SA and how visualization relates to it. In order to identify design limitations in current alarm visualizations, the next section reviews prior work on alarm-visualization design research. Afterwards, underpinned by design principles related to SA, alarm management, and visualization, a set of design considerations and conclusions are provided for further discussion.

2 THEORETICAL BACKGROUND

As aforementioned, it has been widely established that SA is a contributing factor to many accidents and incidents in a variety of HSC contexts. However, defining exactly what constitutes SA has been a challenging task because of the complexity on characterizing the construct in terms of a set of psychological processes (Greitzer et al., 2008).

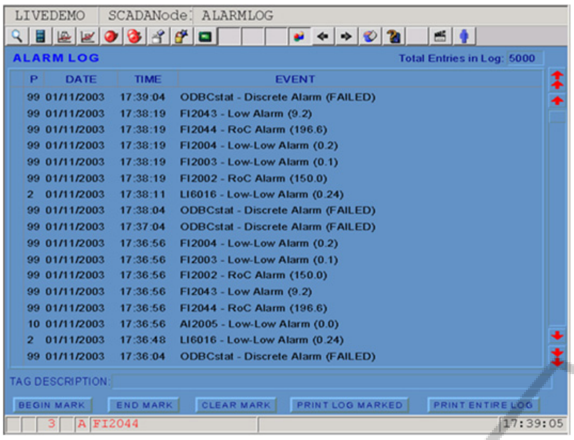
Rousseau, Tremblay, and Breton (Rousseau et al., 2004) performed a systematic classification of 26 SA definitions in the literature. These definitions can be classified in two main classes corresponding to what is now a generally accepted duality of SA as a *state* or a *process*. On the one hand, Mica Endsley has supplied the most highly recognized descriptive model of SA. This definition refers to SA as “the perception of 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” (Endsley et al., 2003, p. 13). Accordingly, Endsley describes this concept as a state of knowledge and the associated process as situation assessment. On the other hand, Dekker and Lutzhoft (Dekker and Lutzhoft, 2004) take issue with the empiricist view of SA that consider SA as a label for a range of cognitive processes or processing activities. They describe SA as an intrinsic feature of the functional relationship between the environment and the person. This approach is highly related to current ideas about *sensemaking* as an active strategy for dealing with a complex world. Sensemaking is the cyclical process in which humans collect information, examine, organize and categorize that information, isolate dimensions of interest, and use the results to solve problems, make decisions, take action, or communicate findings (Klein et al., 2006).

This latter SA perspective is consistent with current ideas about sensemaking as the research path of visualization. According to Stuart Card (Card et al., 1999), the era of pure visualization is over. Leaving aside communication purposes, the goal of visualization should be insight or, more particularly, sensemaking. Visualization can enhance the sensemaking cycle by reducing search; enhancing the recognition of patterns; supporting the easy perceptual inference of relationship; allowing for the perceptual monitoring of a large number of potential events; enabling the exploration of a space of parameter values; and providing means for evaluating various hypotheses (Card et al., 1999; Thomas and Cook, 2005).

3 ALARM VISUALIZATIONS DRAWBACKS

So far, alarm-visualization design research has mainly been focused on developing *presentation-oriented alarm visualizations* instead of reinforcing the analytical strengths naturally gained by the visualization itself. In particular, past research performed by Mattiason (Mattiasson, 1999), Tuszynski (Tuszynski et al., 2002), Bullemer (Bullemer et al., 2011) and Mikkelsen (Mikkelsen et al., 2011) highlights deficiencies related to: (1) *the lack of visual scalability* - the capability of visualization tools to display large datasets, in terms of the number of individual elements and data dimensions (Eick and Karr, 2002); (2) *information integration* - the capability of visualization tools to integrate heterogeneous information spaces into a single analytic environment (Thomas and Cook, 2005); and (3) *support for pattern extraction tasks* - the capability of visualization tools to organize data by structural relationships such as space and time (Thomas and Cook, 2005).

Regarding to visual scalability deficiencies, alarm visualizations have the potential problem of alarm flooding during large disturbances. Alarm flood is a situation where the alarm activations occur so rapidly that the operator is “flooded” by them (Rothenberg, 2009) so the most important alarms are difficult to locate by control room operators.



P	DATE	TIME	EVENT
99	01/11/2003	17:39:04	ODBCstat - Discrete Alarm (FAILED)
99	01/11/2003	17:38:19	FI2043 - Low Alarm (9.2)
99	01/11/2003	17:38:19	FI2044 - RoC Alarm (196.6)
99	01/11/2003	17:38:19	FI2004 - Low-Low Alarm (0.2)
99	01/11/2003	17:38:19	FI2003 - Low-Low Alarm (0.1)
99	01/11/2003	17:38:19	FI2002 - RoC Alarm (150.0)
2	01/11/2003	17:38:11	LI6016 - Low-Low Alarm (0.24)
99	01/11/2003	17:38:04	ODBCstat - Discrete Alarm (FAILED)
99	01/11/2003	17:37:04	ODBCstat - Discrete Alarm (FAILED)
99	01/11/2003	17:36:56	FI2004 - Low-Low Alarm (0.2)
99	01/11/2003	17:36:56	FI2003 - Low-Low Alarm (0.1)
99	01/11/2003	17:36:56	FI2002 - RoC Alarm (150.0)
99	01/11/2003	17:36:56	FI2043 - Low Alarm (9.2)
99	01/11/2003	17:36:56	FI2044 - RoC Alarm (196.6)
10	01/11/2003	17:36:56	AI2005 - Low-Low Alarm (0.0)
2	01/11/2003	17:36:48	LI6016 - Low-Low Alarm (0.24)
99	01/11/2003	17:36:04	ODBCstat - Discrete Alarm (FAILED)

Figure 2: Alarm messages list from a typical SCADA system interface (Broadwin Webaccess, 2012).

Concerning information integration, since current alarm visualizations have different purposes of information, operators have to navigate across them in order to get a unified view of the controlled process condition and, consequently, to establish relationship between alarms. Unfortunately, such limitation can cause that control room operators to get trapped in a phenomenon called attentional tunnelling (Endsley et al., 2003). When people process information from multiple sources, they may lock in on certain aspects that they are trying to process, and will inadvertently drop their scanning behaviour. Finally, regarding to the lack of support for pattern extraction tasks, some alarm visualizations such as alarm messages lists (see Fig. 2) tend to be too detailed with the presentation of sequential information but less comprehensive with the functional organization necessary to understand the nature and progress of a disturbance.

In summary, existing alarm visualizations do not properly assist operators in the process of deciding the condition or situation that motivated the alarms, which can cause operating inefficiencies or even critical operating problems.

4 SA-ORIENTED ALARM VISUALIZATION

Given the significance of SA as a key factor in HSC environments, and considering the analytical strengths provided by visualization itself, the position of this paper is that the fundamental purpose of alarm visualizations should be extended to the assistance of the control room operator's SA. This new design perspective may reveal new insights that overcome human information processing limitations and, therefore, improve the ability of diagnosis of control room operators. Nevertheless, the achievement of this goal should involve the appropriate design decisions.

To create effective alarm visualizations, it must be addressed a number of design questions: *How should the alarms be presented to the operator? How much information can be acquired in the limited available time? How it accurately can be acquired? What is the degree to which that information is compatible with the operator's SA needs? What characterizes effective visualization techniques?* Towards this aim, in what follows, a set of design principles related to alarm management, SA-oriented design (SAOD), and visualization are reviewed. Afterwards, a set of considerations for designing SA-oriented alarm visualizations is provided.

4.1 Principles for Alarm Visualizations

When an alarm is triggered, the first step for control room operators is to identify its typology, severity, and state. Aiming at assisting such detection phase, it is necessary to take into account the following key alarm presentation design guidelines proposed by the two main standards for designing alarm systems, International Society of Automation and the Engineering Equipment [ISA] (2009) and Materials User's Association [EEMUA] (1999):

- *Main alarm visualization shall be provided.* The main alarm visualization should support the task of monitoring and controlling the future behaviour of the process by attracting the operator's attention towards process conditions that require assessment or action.
- *Key alarms shall be shown in overview displays that are permanently on view, with spatially dedicated alarms.* The purpose of key alarm visualization is to improve the management of alarm overloads. Key alarm visualizations ensure both an information rate and a presentation form that will remain manageable under all process conditions.
- *Special visual annunciation should be used for new alarms.* Visual annunciation is used to attract operator's attention towards new alarms and distinguish them from alarms that have been accepted.
- *The priority of alarms should be coded using colours and possibly other means.* This is to ensure that different priorities are visually separated in a way that makes it very quick and

easy to spot the most important alarms among the less important ones.

4.2 Principles for Situation Awareness-Oriented Design

The way in which information is presented to the operator through the interface greatly influences SA (Endsley et al., 2003; Rothenberg, 2009). The most applied principles for creating SA-oriented designs are the fifty design principles proposed by Endsley (Endsley, 1995; Endsley et al., 2003). These principles are based on a model of human cognition involving dynamic switching between goal-driven and data-driven processing and feature support for limited operator resources. However, they underpin not only SA design interface issues but also how to design automated systems, dealing with complexity or uncertainty. For this reason, the set of principles to consider for designing effective alarm visualizations should be reduced to those focused on the interface design.

- *Goal-oriented information displays.* Goal-oriented information displays should be provided, organized so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal.
- *Direct presentation of higher-level SA needs rather than supplying only low-level data that operators must integrate and interpret manually.* As attention and working memory are limited, the degree to which displays provide information that is processed and integrated in terms of comprehension and projection will positively impact SA.
- *Support for global SA.* Providing an overview of the situation across the operator's goals at all times and enabling efficient and timely goal switching and projection.
- *Critical cues related to key features of schemata need to be determined and made salient in the interface design.* In particular those cues that will indicate the presence of prototypical situations will be of prime importance and will facilitate goal switching in critical conditions.
- *Support for parallel processing.* Multi-modal displays should be provided in data rich environments.
- *Use information filtering carefully.* Extraneous information not related to SA needs should be removed (while carefully ensuring that such information is not needed for broader SA needs).

4.3 Visualization Design Principles

Visualization can be understood as "the process of designing information to match the processing characteristics of human visual system" (Zhang et al., 2002). Consequently, a first step in developing effective visualizations is to understand how they enable perception and cognition. The achievement of this purpose encompasses the application of the following set of visualization design principles (Mackinlay, 1986; Norman, 1993; Card et al., 1999; Tversky et al., 2002).

- *Appropriateness principle.* Visualizations should provide neither more nor less information than that needed for solving the problem.
- *Naturalness principle.* Experiential cognition is most effective when the properties of the visual representation most closely match the information being represented. This principle supports the idea that new visual metaphors are only useful for representing information when they match the user's cognitive model of the information. Purely artificial visual metaphors can actually hinder understanding.
- *Matching principle.* Representations of information are most effective when they match the task to be performed by the user. Effective visual representations should present affordances suggestive of the appropriate action.
- *Principle of congruence.* The structure and content of a visualization should correspond to the structure and content of the desired mental representation. In other words, the visual representation should represent the important concepts in the domain of interest.
- *Principle of apprehension.* The structure and content of a visualization should be readily and accurately perceived and comprehended.
- *Principle of expressiveness.* The visualization contains all the facts in the data set and only the facts.
- *Principle of effectiveness.* The visualization conveys the information in an effective way.

4.4 Design Considerations

Through the use of cues generated by alarm visualizations, SA in HSC environments involves to effectively perceive, fuse and relate the relevant alarm from large volumes of divergent multi-source, multi-dimensional, and time-varying alarm streams (Sheridan, 1992; Nachreiner et al., 2006). The body of prior work related to SA, alarm management, and visualization has led it to formulate desired properties and future directions for the design of alarm visualizations that assist the achievement of the control room operator's SA. As a result, dynamic interaction and exploration capabilities are proposed in this paper as crucial design considerations for the effectiveness design of alarm visualizations in HSC environments.

Overview alarm visualization for collecting information: Data and visualization attributes. The first stage of sensemaking cycle is related to information foraging. With the purpose of assisting this phase, displaying an overview of the current condition of the controlled process at all times should be essential. Building on pre-attentive visual processing such as colour and position, overview alarm visualization may provide a starting point for recognizing and flagging events that require further analysis. The most important attributes to include in this visualization should be related to the alarm state, alarm priority and alarm typology (EEMUA, 1999; ISA, 2009). Alarm state is referred to both the operator acknowledgment and the state in which the controlled process is operating (ISA, 2009). Alarm priority is defined as the importance assigned to an alarm within the alarm system to indicate the urgency of response (ISA, 2009). Finally, alarm typology is described as a group of alarms with common alarm management requirements (ISA, 2009). Since these attributes are well suited to provide an overview of the condition of the controlled process, the alarm may be provided in a drill-drown detail view to support later analysis.

Multiple views and levels of data. The analysis and diagnosis tasks of the current condition of the controlled process require assistance for operator exploration. The operator wishes to understand trends, locate anomalies, isolate and re-organize information, compare, and make clear any differences or similarities between datasets in order to develop a hypothesis (Rothenberg, 2009). Therefore, the need of overview visualizations for quickly identifying an alarm in collecting information phase should be replaced by a need of alarm visualizations that are linked and arranged and can represent multidimensional data from multiple sources.

Filtering and distortion methods. While perception of important alarms require as little user interaction as possible, supporting analysis tasks is a much more interactive activity. Due to the large size of the data sets, in particular, during large disturbances, filtering should be a very important function. Filtering could become in both a transitional mechanism from detection to comprehension phase and a mechanism for increasing the visual scalability of alarm visualizations. At the same time, as the data that is not the focus of the task is still important in providing vital contextual information (Endsley et al., 2003), distortion methods (Eick and Karr, 2002) should be applied to highlight relevant alarms without necessarily removing from the alarm visualization. Distortion methods allow users to examine one or more local areas in detail, in the context of a global view of the space (Andrienko et al., 2003).

Pattern recognition. The analysis and diagnosis of an abnormal situation cannot be accomplished without also taking into account certain patterns of alarm activations that can supply new sources of information to control room operators. A pattern is understood as an arrangement or form, a model or plan. In HSC environments, to observe that certain patterns of alarm activations not only announce a set of individual problems but, when taken as a group, can also suggest more complex problems with clarity (Rothenberg, 2009). Therefore, effective alarm visualizations that support pattern recognition tasks must fuse disparate data sources together seamlessly, that can correlate all of the data together.

5 CONCLUSIONS

The use of alarm information in HSC environments should go further than the purpose envisioned by early alarm system designers. As related research on alarm systems design has established, control room operators should use alarm visualizations as a support for diagnosing and making decisions about the condition of the controlled process. On the contrary, current alarm visualizations have several design limitations for assisting this decision-making process. Making the shift to this design perspective may enable control room operators to improve their ability to diagnose the causes of abnormal situations and, therefore, the overall effectiveness of HSC tasks.

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