Improving Control Room State Awareness through Complex Sonification Interfaces

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Abstract. Across a number of complex control room settings, there are concerns regarding operator information overload and alarm flooding. The evolution of control room technological capabilities has accelerated in recent years, due to drastic improvements in computer processing power, speed, and sensor integration. However, aging infrastructure and retiring senior operators in legacy control room systems such as chemical and power generation plants have begun to create opportunities for once-per-generation improvements in control room interface capabilities. Additional facilities, including power grid interconnection centers and computer network security monitoring centers, have created new generations of network operations control centers (NOCs). The authors' work is emphasizing the development and application of audification and parameter mapping techniques to generate engineering-based principles for presenting state-based auditory information to plant or NOC operators. There are no current systematic engineering-based principles used to apply sonification to control rooms or engineering system states in a clearly standardized way. Our current work in this domain examines the critical parameters that control room operators recognize and monitor in order to get a "sense of the plant" in nominal, degrading, or hazardous states. Principles and parameters for implementing these sonification techniques for power plant and NOC contexts are presented and discussed.

1 Introduction

Efforts to improve the design and implementation of human-machine interfaces for industrial control applications far predate the rise of the computer age. However, with the advent of digital computers, the scope and capability of control room information presentation to operators has increased substantially. The control and management of complex computer network operations themselves has now become an area of concern, especially due to issues of software network breakdowns, intentional attacks, and naturally occurring events that can threaten both physical and information infrastructure operations.

Distinct challenges face designers and operators of legacy control rooms (such as those for chemical processing, surface transportation, or power generation plants) and those of more modern systems (such as "cyber-operations" centers for civilian or military information networks). In the case of legacy control rooms, massive

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installed hardware systems and regulatory oversight requirements result in major technology and cost barriers associated with any new implementation of control room interface designs. As a result, many legacy systems are subject to very slow upgrade cycles, measured in years (if not decades) between generations of control room interface technologies. In the case of nuclear power plants in the US, for example, almost all plants currently operating are based on control room designs of the 1960s and 1970s. While some improvements have been made in display technologies, widespread implementations of new computer processing systems in such plants still greatly lag current capabilities of consumer-grade computer technologies. A particular gap exists in the use of complex sound signals to provide operators of infrastructure and network operations centers (NOCs) with information about the current state of critical plant parameters. For the remainder of this paper, we will use the term *sonification* to refer to the use of computer-generated audio signals to provide information to human operators about the state of a computer-monitored system or other dynamic process.

The goal of our present work is to investigate how to design and implement principle-based guidelines for sonification to provide improved information to control room operators to forestall, minimize, or even prevent adverse event outcomes in cyber-network or other high consequence infrastructure operations. By principle-based, we focus on combinations of systematic engineering, mathematical, music theory, and psychological processes that can be generalized across process dynamics and event progressions. Our initial focus is on the development of these guidelines in the context of a specific operational context: control and monitoring of a nuclear power generation facility.

2 Alarm Management vs. State Awareness

Alarms systems are intended to provide important support in the human operator's abilities to monitor and control an engineering infrastructure system. Audio alarms allow detection of whether a process or state is beyond acceptable limits (as defined by alarm thresholds). Reductions in costs for both sensor technologies and audio processing technologies have resulted in increase use of distributed alarms and audio alarm presentations in supervisory control environments. The management of audible (and visual) alarms in control room and other settings has become a major focus of human factors and process control management research (Sarter and Woods, 1995; Woods and Sarter, 2010).

One ongoing concern is that of "alarm flooding". Alarm floods occur when the number and timing of alarms presented to the operator interferes with (or, in some cases, actually prevents) the operator's ability to determine the current state of the engineering system and select / execute appropriate responses to return the system to a desirable state. Substantial advances have been made to the field of alarm management over several decades (Baldwin, 2012; Xiao and Seagull, 1999). However, research into human performance modeling has shown that the limit of operator abilities is approximately 10 alarms per 10 minute period (Reising, Downs, & Bayn, 2004). The Engineering Equipment and Materials User Association's (EEMUA) suggests an average alarm rate during normal operations of one alarm per 10 minutes (EEMUA, 1999), but rates of over three alarms per 10 minutes are common (Reising and Montgomery, 2005). This over-occurrence of alarms leads to operators using up limited resources, not only to both separate and manage these different alarms, but also to respond to the real conditions they represent.

When faced with alarm floods, operators are required to create and execute strategies to deal with limited and declining resources. They must detect, differentiate and manage the alarms themselves, and respond to the (uncertain) conditions represented by the alarms. Operators can become tentative or confused as they try to resolve individual alarms and their events. This confusion can also result from masking high-priority alarms with low-priority ones. Some operators may seek to manually bypass certain alarms and view them as "nuisance alarms" or those not critical to operations. As control room operators become exposed to ongoing levels of alarms that lose distinctive importance to identify adverse or emergency situations, they may even become conditioned to alarm floods, failing to give the alarms their due importance (see Koene & Vedam, 2000). Over time, alarm flooding can cause irritability, stress, confusion, or even panic among operators (Baldwin, 2012).

In order to provide improved state awareness using audio signals, there is first the question of recognizing and identifying how to present engineering system state information through computer-based audio signal processing technologies. Xiao and Seagull (1999) point out that there is a lack of general understanding of the actual information (meaning, not just signal detection) contained in an audio warning. In a variety of environments, humans and other animals use very complex audio signals to determine state, threat, and other dynamic conditions through localization and other techniques. Music is an apparently universal aspect of human experience, and the creation and appreciation of music has a number of complex features with both physiological and emotional meaning for behavior (Levitin, 2006). Rhythm, tonal quality, and other features of musical expression can be seen as a form of structural and temporal alignment in human cognitive processing (Bharucha, Curtis, and Paroo, 2012). Some authors even suggest that training paired with listening to music can increase attention and mindful awareness of flow (increased cognitive integration) (Diaz, 2013). These insights indicate that computer-based sonification interfaces, as well as an integration of engineering and music principles to tie system state to musical expression, can be used to improve operator awareness of engineering system state prior to the degraded conditions where alarm floods begin.

3 Forms of Sonification

Researchers in the area of sonification differentiate four distinct forms of providing system state or behavior information via audio signals (Hermann, Hunt, and Neuhoff, 2011). The first type, ***auditory icons***, frequently use learned associations of sounds with particular artifacts (often legacy mechanical objects whose sounds were a necessary element of the prior system's operation). For instance, the electronically created sound of a camera shutter on a smartphone, or the sound of a clicking turn signal in a modern vehicle, are no longer due to the mechanical leaves or relays that created the original sound. However, because users now associate those sounds with the function of taking a picture or activating a turn signal, the auditory icon continues that association. In a similar fashion, ***audification*** represents the direct translation of a engineering or physical process into an audio trace. The click of a Geiger counter and the sound of static and tones in an analog radio represent characteristics of the physical world translated and processed in the audio spectrum.

By contrast, the ***earcon*** has been created distinctly to represent, as an audio symbol or trigger, a particular reference item. Tonal trademarks, such as the NBC or Intel logos, or theme representations associated with musical pieces (the opening notes of Beethoven's Fifth Symphony, the shark theme from *Jaws*) represent such audio symbols. The fourth type of sonification is described as ***parameter mapping***, where naturally occurring engineering system parameters can be translated into sound notations or musical forms. For instance, imagine a power generation turbine rotating at 2000 rpm. A parameter mapping sonification of such a turbine in a control room could be represented by a flute playing at 2000 Hz. The sound of this turbine as perceived by an operator standing next to it may not hear a sound that directly represents a flute or other instrument at 2000 Hz. However, the mapping of 2000 rpm to 2000 Hz represents a straightforward parameter mapping.

Some sonification elements represent combinations of audification and parameter mapping. The musical compositions included in *IBM 1401: A User's Manual* (Johannsson, 2006) include tracks of the computer's magnetic memory causing interference with nearby radios (audification), but the orchestral representations of the rhythms and tones that comprise harmonies with the original memory tracks could be created as parameter mapping. (Such parameter mapping was not explicit, either contemporaneously or later: programmers could create "music" by writing computer programs to access memory in particular patterns, but there was no music created to indicate other aspects of computer memory usage or storage capacity.)

Timbre and rhythm are complex elements of a multidimensional perceptual process in human auditory behavior, a factor that has been researched in the psychological and human factors communities for decades (see Licklider, 1951 cited in Grey, 1977). However, as Grey (1977) has indicated, direct training on mapping timbre (sound profile) to specific instruments based on patterns of overtones and resonant frequencies is not easy for most human listeners. These types of findings suggest that parameter mapping or audification of very complex, fine grained distinctions between system parameters to specific instruments in a large orchestral representation may degrade, rather than enhance, the operator's ability to quickly discern subtle changes in system state. Context and expectation—the features that enable the listener's recognition of jazz syncopation or "hesitation" waltz forms—are additional elements of music and sound perception over time, which need to be studied with attention to serial correlation and sequences of musical phrases or movements (Schubert, 2002). Tempo and rhythm factors are important in expertise coordination context, especially when delays and information flow lags significantly affect expectations of the arrival of information or task updates (B. S. Caldwell, 2008).

The capacity to provide multi-dimensional and multi-function information to computer users in the audio domain has demonstrated considerable advances in recent years. Unlike designers and operators of NOC control rooms, computer and video game designers have quite actively exploited advances in computer-based audio processing to provide sonification and other audio information to game players. Immersive and realistic audio representations (thus incorporating auditory icon and audification techniques) as well as audio representation of game play status (representing parameter mapping) have been strong elements of maintaining player awareness and enjoyment in "first person shooter" video games (Grimshaw, 2008; Grimshaw and Schott, 2008). For these researchers, the characteristics of sound generated by objects in the game (as opposed to music soundtracks) are described as "diegetic" sound (Nacke, Grimshaw, and Lindley, 2010). (This description of diegetic sound seems to directly suggest at least auditory icon and audification elements of sonification, using either pre-recorded or computer-generated object representations. Game status (threat level, player health, etc.), while possibly musical in form, is more correctly described as parameter mapping diegetic sonification, rather than non-diegetic soundtrack music.) The process of generating diegetic sounds in computer games in order to enhance player state awareness and immersive gameplay experience appears to have a strong parallel to providing sonifications of engineering state for NOC and other control room operators.

4 Next Steps: Determining NOC Parameters and Principles

Digital signal processing and audio generation technologies are no longer the technological barrier to providing rich and robust audio interfaces to control room operators. Substantial work with users in computer game environments have demonstrated these users' immersion, performance, and usability effects both within game play and in task transfer settings (Chiappe, Conger, Liao, J. Caldwell, and Vu, 2013). In order to improve effectiveness and generalizability of control room design, however, systematic descriptions of engineering, mathematical (music form), and musicality (music perception) principles need to be applied to sonification efforts in audification and parameter mapping.

Our current work in this domain examines the critical parameters that control room operators recognize and monitor in order to get a "sense of the plant" in nominal, degrading, or hazardous states. Being able to transform these parameters into coherent auditory orchestrations to indicate current operational state is the near-term goal of this work. As parameters deviate in a continuous fashion from set points, mapping of those deviations in terms of rhythm, tone, and/or relative strength of instrumental mix can allow operators to monitor plant state in an omnidirectional, easily learned auditory format.

Statistical process control techniques can be used to increase volume of the sonification gradually and noticeably with increasing deviation from setpoint, rather than simply at threshold crossing past a control limit. Techniques for allowing human operators to determine and respond to control limit transitions as a performance enhancement and workload management strategy for improving state awareness and task effectiveness have been a goal for some time (B. S. Caldwell, 1997; Tulga and Sheridan, 1980).

Pilot interviews with nuclear and other power plant control operators have already begun, in order to identify the primary (quantitatively varying) plant state parameters of greatest importance to control room operators when monitoring plant health. Although detailed mapping of many parameters to specific instruments is problematic (Grey, 1977), relatively simple mappings of 3-6 critical plant parameters to instrument "families" in an orchestra (strings, brass, percussion) seems feasible. The specific mappings depend on the frequency and rhythmic nature of those parameters, but can be validated with cognitive walkthrough and perception-based usability evaluation techniques. In order to further increase the principle-based generalizability of this approach, the first author is also leading a study to conduct a similar research approach to identify critical cyberinfrastructure network parameters of importance to experienced NOC operators. There is still a strong need to determine the presentation of these parameters for NOC information *visualization*. However, the very high event rates of network flows or intrusion detections suggests that audification and parameter mapping techniques using similar parameter identification techniques have great promise for designs of NOC information *sonification*.

These techniques have substantial potential benefits over traditional alarm techniques, including proactive information presentation based on system state rather than sensor threshold crossing. The ultimate purpose of this research is not simply to improve alarm integration or reduce the sheer number of alarms impinging on operators during emergency situations. Proactive and forecast information highlighting sonification of NOC state trends can in fact forestall or even prevent some alarm state conditions from occurring. Increased sensemaking and critical parameter identification to operators can support more rapid determination and troubleshooting behaviors prior to the onset of emergency system conditions.

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