A Survey and Comparison of Human Monitoring of Complex Networks†

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***Abstract*— Networks of different types are essential infrastructures for society. Networks such as transportation networks and the electric power grid are becoming increasingly large and complex which create special challenges for human operators who must monitor these networks for safe operation. It is important to understand how human operators monitor these networks and the challenges they face in the monitoring task. In order to do this, we conducted a survey of how human operators monitor various networks—water distribution networks, electric power grid, air traffic control, and nuclear power plant networks. From our survey in these specific extensively-studied networks, we are able to generalize the challenges of operators monitoring networks. The hope is that these results will provide human factors engineers with a better understanding so they can cater to the needs of the human operators when designing new interfaces for network monitoring tasks.**

Keywords: network monitoring, human factors, visualization

I. INTRODUCTION

Networks that enhance our quality of life are increasingly becoming more complex in size, speed, and functionality with the advent of technological advances. Because these networks are interdependent, all these infrastructures are built upon underlying computerized systems that are interconnected; they cannot be studied completely in isolation.

These dimensions of network complexity have many implications. In this paper we focus on the problem of human monitoring of increasingly complex networks. Human monitored networks are prone to adverse consequences because human cognitive abilities to perceive, understand, decide, and react do not scale in the same way as network size, speed, and functionality.

How well networks are monitored by human operators not only has a great impact on the productivity of these networks but also on safety—in fact eight of these networks have been labeled critical infrastructures for special protection[1]. Because of this, it is important to understand how human operators monitor these networks—the tasks that they perform, the challenges they face, the current tools that they use. Using this information, designers can then create interfaces that enhance the human operation to be more successful at monitoring the network—alleviating information overload, integrating information, highlighting information, decreasing response time and increasing effectiveness.

In order to understand how human operators monitor these complex networks, we conducted a literature survey that examined various complex networks and the tasks involved in monitoring the network, the current tools used, and the challenges operators face. As a result of this survey, we have identified common challenges and addressed design implications for monitoring such networks.

The remainder of this paper is organized as follows: Section II defines terminology and the scope we will be investigating. Section III is a detailed literature survey of four different networks. Section IV discusses insights gained from the survey information in terms of common and contrasting issues. We end with a summary and conclusions in Section V.

II. DIFFERENT TYPES OF NETWORKS

For the purposes of this paper, we define a network as an interconnecting collection of processing nodes and transmission links that change dynamically over time to move some entity (i.e. electricity) from one point to another as efficiently as possible within a budget constraint.[2] A network can be represented with two types of information: (1) the topology or structure of interconnecting nodes and links and (2) associated weights on each node and link corresponding to costs, capacity, supply demands, etc. The general area of networks can be categorized into smaller and more specific type of networks. For example, in our study of human monitoring of networks, the following types of networks arose—process intensive and node intensive. A process intensive network requires a relatively high amount of manipulation and processing of data, whether at a given node or processing across edges, such as the air traffic control network. The information about each individual aircraft needs

[1] Presidential Executive Order on Critical Infrastructure Protection 13010, Federal Register, July 17, 1996, Vol 61 No 138, pp. 37347-37350. The eight critical infrastructures listed are: (1) Telecommunications, (2) Electric Power Systems, (3) Gas/Oil Storage/Transportation, (4) Banking and Finance, (5) Transportation (surface and aviation), (6) Water Supply System, (7) Emergency Services (Fire & Rescue, Law Enforcement, Public Health), and (8) Continuity of Government.

[2] Adapted from *Network Flows: Theory, Algorithms, and Applications* by R. Ahuja, R.L. Magnanti, J.B. Orlin, Prentice Hall, 1993.

to be processed, integrated, and constantly updated in the system to give air traffic controllers the overall picture of a specified area of air traffic in real-time; thus, there is an intensive processing requirement at specific nodes. Similarly, a node intensive network is a network in which there are a large number of nodes in a network. For example, a nuclear power plant can be viewed as a collapsed network of nodes that provide measurements and data values to operators about the state of the plant.

Much work has been conducted to aid human operators improve productivity, reduce response times, and be more vigilant for each of the networks we will examine. However, there has been little, if any, work seeking to find common tasks between monitoring of different types of networks.

III. HUMAN MONITORING SURVEY

We chose to conduct a literature survey in the areas of water distribution systems, electric power grids, air traffic control, and nuclear power plants. Each of these networks has been extensively studied and we draw on this research. For each network we identify: (1) the monitoring task that a human operator performs, (2) the current tools that are being used by the operators, (3) the challenges that the operators face in performing their monitoring task, and (4) proposed solutions to aid the human operator. We present the networks in approximate historical order to emphasize the evolution of human network monitoring in different contexts.

A. Water Distribution Systems

Monitoring Task(s)

The day-to-day operation of a water system network is typically the responsibility of one to two plant operators, in addition to assistants, who are on duty at all times at the treatment plant. Their main task is to monitor the quality of water as it enters the distribution system. Typically, this monitoring is not performed in real-time except for monitoring pressure levels (i.e. to catch water main breaks) and sometimes chlorine residual levels [1].

In addition to monitoring water plants, the water system needs to deliver clean water and, conversely, prevent drinking water contamination [2]. In order to prevent contamination, the United States is now moving towards the use of real-time monitoring of water distribution sites due to security concerns as well as improvements in real-time water monitoring equipment. Operators need to reliably identify low probability/high impact contamination events in source water or distribution systems in order for a timely and effective local response that avoids or mitigates adverse impacts [2].

Current Tools

The operational monitoring and control of water systems is handled with Supervisory Control and Data Acquisition (SCADA) systems. SCADA can have a graphical interface component that shows a general system overview as well as specific details such as reservoir and water tower levels, status

FIGURE 1. WATER PLANT CONTROL ROOM
<http://www.oswego.edu/prosmart/PROJECTS.HTM>

of pump stations, filters, tanks, pressure gauges and other components linked by pipes.

Because monitoring of drinking water for contamination is not required, there are currently no tools being used in water distribution plants for real-time monitoring of the water drinking quality; however, much research is being conducted in this area.

Challenges

There are many challenges to real-time water system to monitoring. One big challenge is determining the number of monitoring stations needed to accurately detect the contamination of the drinking water. Though the likelihood of detecting contamination increases with more monitoring stations, there is a tradeoff of diminishing returns—the amount of detection gain diminishes with each new monitoring stations [3]. In addition, as the number of monitoring stations increases to a certain level, the information provided will often be redundant increasing both information overload and decreasing the percentage of relevant information [3].

Another challenge for the monitoring of a water system is the need for operators to verify what is happening when a contamination occurs against what is predicted in a computational model [2]. Not only do operators need to identify and verify contamination, but they also need to identify the point of intrusion from information provided by monitoring stations [4].

Proposed Solutions

Computer modeling can be used to find the optimal layout and number of monitoring stations for a water system which can reduce the cognitive demands of operators [4]. An optimal infrastructure design will more effectively track and potentially contain contamination throughout a water distribution system [4].

To aid operators in the task of real-time monitoring of a water network, a system was created that automatically validates information from mathematical hydraulic and water quality model with that of the data gathered by the SCADA system, MIKE-NET-SCADA [2]. MIKE-NET-SCADA takes data from the SCADA system to validate against a model. With an integrated modeling approach, the monitoring of hydraulic conditions in the water distribution network can be automated allowing an operator to concentrate on monitoring entire water network operation instead of focusing on local data from a limited number of SCADA sensors [2]. Additional benefits include an enhanced ability to process larger amounts of information in a shorter time and emergency responsiveness.

B. Electric Power Grids

Monitoring Task(s)

Power grid operators have many tasks in their day-to-day monitoring of the grid. The three main monitoring tasks are: (1) monitoring sensor data from power grid components (bus voltages, bus numbers, status of the capacitors, transmission lines, transformers, circuit breakers, etc.), (2) monitoring the grid as a holistic system, and (3) responding to alarms [5].

Current Tools

To obtain an overview of the status of the grid, operators use a map board. The map board is static map of the overall system, but the data is dynamic and displayed using different colored lights [6]. In addition, the map board also displays the status and alarm conditions of individual transmission elements [7]. Because the map board only provides an overview of the grid, the map board is then supplemented by computer displays that show system measurements using a combination of data tables and vector-based graphics [7].

Traditionally, the computer displays that provide a more detailed picture of the plant use tabular list displays, one-line diagrams, or contour diagrams to display data [5]. A tabular list is a list of tables that display various pieces of information about the grid—bus voltage magnitudes, status of the capacitors, and line outages. All the information that is presented by a tabular list is text-based, but the text may be displayed in another color (i.e. red) if it exceeds or falls below a certain threshold [6]. One-line diagrams are diagrams of the system showing the buses and the bus voltage magnitude associated with the bus. If the bus voltage falls beneath a certain voltage, the bus becomes red [6]. Contouring diagrams are the same as one-line diagrams, except the bus lines are colored coded based upon the voltage and the color contour associated with that particular number [6].

Challenges

Because a power grid contains so many different parts and connections between the parts, the monitoring task can be especially challenging for an operator. The operator not only needs to monitor the equipment and status of the equipment, but they also need to understand how the equipment flows and how they are interconnected [7, 8]. Because of this need to see an overview and also the details of the grid, one big challenge is integrating an overview and detailed context of the grid to give an operator the maximal information without overload. This requires a balance of understanding what information is pertinent to display in the overview and the detailed context for the operator and what information would cause information overload. Currently, the overview of the plant is provided through the board map that contains little or no numerical information, and the detailed context is located on separate displays for individual substations [7]. Even with the overview and context displays, it is difficult and unlikely that all data can be presented to an operator due to the lack of real estate on various displays [9].

FIGURE 2. ELECTRIC POWER GRID CONTROL ROOM
<http://msnbc.msn.com/id/3077316/>

Another challenge that arises is how the information is presented to the operator. The first part of data presentation is to determine the layout. Many plants use a data display driven primarily by the structure of the power system. Specifically, the data appears grouped by geographic proximity in the power system [9]. Using this display structure has a tradeoff between context and task. The use of this layout provides an operator context of the data and the ability to understand the relationship between pieces of data. Unfortunately this layout can reduce the efficiency and productivity of an operator because this layout can require an operator to look at data scattered throughout the system to perform a particular task.

Another challenge is how to effectively display the data to the operator so that they can perform the monitoring tasks effectively and efficiently. Data can be displayed by the use of numbers, colors, diagrams, or any combination of the three. Depending on the needs of the operator, certain display presentations maybe better than others. For example, displaying data solely using numbers allows an operator to obtain exact information, but it requires many steps for the operator to assess the state of the plant—reading the value, consulting a table of values to retrieve the limits that define the state for the specific situation, comparing the values received from the display with that in the table, and finally determining the status of the value [8]. The use of numbers also makes it difficult for an operator to identify trends in the system to assess the system's behavior. Moreover, displaying data based solely on color may allow operators to assess the state of the system more quickly. There is a disadvantage to using only color in the displays because it can be more difficult and time consuming to resolve any problems that arise because of the lack of specific data. In addition, data can be presented through diagrams of the system which is generally coupled with numerical data. This allows for an operator to identify specific parts of the system that needs immediate attention when a problem arises as well as the specific data values.

Proposed Solutions

The challenges that arise from monitoring a power grid are related to retrieving and presenting the data from the system. In order to alleviate the overwhelming amounts of information for operators, research has been conducted on integrating the data into different forms for operators. In particular, research has been conducted in the area of using diagrams and graphical presentation [6]. Research has shown that with visual presentation, users are able to not only detect problems in the system, but are better able to identify and execute the appropriate solution [6]. The reason for this is that human ability to recognize patterns and connections in graphical presentations significantly reduces the amount of cognitive effort required to make decisions [9]. Despite this visual advantage, interface designers for power plant grids still need to determine what information should be presented in the diagrams and how they should be presented.

C. Air Traffic Control

Monitoring Task(s)

There are three different types of air traffic control facilities: (1) the air traffic control tower, (2) the terminal radar approach control (TRACON), and (3) the air route traffic control center (en route center) [10].

The main task of the air traffic control center is to control aircraft on the ground at two critical points—just before takeoff and just before landing. The tasks are usually shared with the ground controller and the local area controller. Specifically the air traffic control towers tasks include (1) clearing aircraft to push back form the gate, (2) clearing aircraft to leave the ground, (3) managing ground traffic to and from the gate and runways, (4) maintaining a safe distance separation between aircraft, and (5) handoff of aircraft with the TRACON controller [10].

The tasks of the TRACON operators are: (1) to manage safe and expeditious flow of departing aircraft accepted from the tower to a handoff to the en route controller, (2) manage the arriving aircraft from a handoff from the en route controller to a handoff to the tower controller on a final approach for landing, (3) sequencing the aircraft in an orderly inbound or outbound flow at a regular spacing, and (5) maintaining a safe distance separation between aircraft [10].

Operators in the en route center need to use the radar

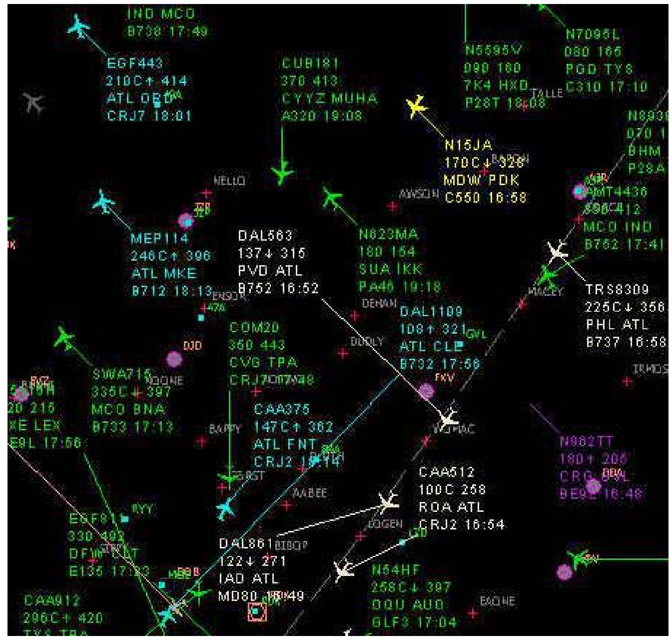

FIGURE 3. NORTHEAST ATLANTA MACEY ARRIVAL SERVICING THE ATLANTA HARTSFIELD JACKSON INTERNATIONAL AIRPORT, ATLANTA, GEORGIA

<http://atcmonitor.com/>

information to provide guidance to flying aircraft. They also need to maintain the expeditious delivery of an aircraft stream to the receiving TRACONs [10].

All air traffic control facilities share the responsibility of monitoring individual aircraft movement with surrounding aircraft. If any problems arise, any of the three air traffic control facilities may alert aircraft pilots to initiate changes from filed plans [11].

Current Tools

With each facility, operators may rely on different tools in order to complete their tasks. Because the air traffic control tower has the most complex tasks in monitoring aircraft, operators rely on a variety of tools: their eyes, communications link, airport surface detection equipment (ASDE), DBRITE, and paper flight strips. Because the main tasks of operators in the tower are to manage the aircraft on the ground as they move from taking off, landing, and taxiing on the ground, operators use their eyes to monitor where the location of aircraft are [10]. Operators also use voice communication link to verify the location of aircraft. When there is reduced visibility, either from weather or nighttime, operators face challenges. Fortunately, the airport surface detection equipment (ASDE) allows operators to monitor aircraft on the ground even when visual contact cannot be made. The ASDE is a system that provides radar identification of ground vehicles and aircraft in an airport. Operators also use DBRITE which is a radar display that augments visual control of the airborne traffic. DBRITE provides the operator with a radar presentation of about fifteen miles around the airport, alphanumeric information on the aircrafts that are received from the automated radar terminal system nearby TRACON, view of arrival aircraft that are not under the tower's control so that the aircraft that are under the tower's responsibility on the ground can be safely and efficiently coordinated with planned arrivals. In addition to these tools, operators also use paper flight strips, which are physical representations of each aircraft, as a visible reminder of an aircraft's status in the sequence of taxi-takeoff.

TRACON operators use a radar monitoring tool, automated radar terminal system (ARTS) that provides information about departing/landing aircraft providing operators a big picture of aircraft movements in his/her assigned area. ARTS also provide TRACON operators with conflict alerts, minimum safe altitude warnings and predict-and-confirm system for aircraft movements. Similar to operators in towers and TRACONS, en route operators also use radar to monitor air traffic.

Challenges

Many of the challenges that arise from monitoring aircraft arise from cognitive vulnerabilities while on-task. In visual sampling and selective attention, controllers are vulnerable to missing critical events through breakdowns in the serial scanning process. When scanning radars, controllers face display clutter, aircraft misidentification, and may not be able to detect unexpected events due to expectations.

Working memory is another area of vulnerability for operators. Working memory is susceptible to interference from competing processes (i.e. speaking will disrupt verbal working memory; visual scanning and search will disrupt spatial working memory). Working memory also suffers when it must retain items that are similar to each other, such as aircraft with similar call signs. Most situational awareness is heavily dependent on spatial working memory to compute future states of aircraft. Calculating the future states of the aircraft can be very taxing on controllers due to the complexity of calculating trajectories from radars, crowding in the airspace, and potential loss of radar data. In addition, other areas of cognitive vulnerabilities include communications, long-term memory, judgment and decision making, and errors [10].

The displays used by controllers can pose as a potential problem area for controllers. One area in particular is the ability to detect traffic conflicts [11]. During conflict detection, controllers rely on the visual display of information to extrapolate of aircraft pair trajectories [11]. This task is made even more difficult if the display overloads the controller with too many aircraft. Furthermore, these displays depend on alphanumeric data blocks for critical information. Because of this, numerous eye fixations and complex mental transformations are required for a controller to form a 3D mental representation of the location and heading of an aircraft [12].

Proposed Solutions

Air traffic monitoring is a very complex task and taxing upon a controller. One way that researchers have been looking at reducing this workload is changing the way in which information is displayed. Research has suggested the use of color coding altitude to reduce the time to detect conflicts in static air traffic control [11]. By doing this, controllers get pre-attentive situational awareness. Research is needed to improve information displays and decrease cognitive vulnerabilities.

FIGURE 4. TYPICAL NUCLEAR POWER PLANT CONTROL ROOM <http://people.howstuffworks.com/nuclear-power4.htm>

D. Nuclear Power Plants

Monitoring Task(s)

Nuclear power plants have thousands of parameters that operators can potentially monitor—the control room of a nuclear power plant typically has hundreds of indicators. The task of monitoring the plant does not merely involve reading indicators and values to see if they fall in a safe threshold. Operators of nuclear power plants need to decide what data and information is relevant to monitor and what deviation or change in these values is meaningful [13]. The monitoring task is dependent upon the prior knowledge of operators such as the unique properties of plant systems and how systems interact [14].

Typically the monitoring task requires operators to answer higher order questions from a single-sensor, single-indicator displays. To answer these higher order questions (i.e. the current state of the plant), operators need to determine which pieces of data are relevant for the current task, gather the relevant data from individual instruments (which are often located on different control boards), and integrate this information mentally to derive the higher-order properties of interests [14, 15].

Current Tools

In [13], a thorough case study was performed to see how nuclear power plant operators monitor the plant and revealed the tools that operators use for their tasks. The primary source of information for monitoring comes from the control room indicators and alarms. The control room panels and CRT displays were found to be monitored on a regular basis by virtually all the operators observed. The CRTs are dedicated to presenting textual alarm messages as a chronologically ordered list. Newer control rooms use the CRTs to display graphs and trends [15]. With the alarm displays, there is an auditory signal accompanied by the onset and offset of an alarm in addition to messages displayed on the CRT. Because of the saliency of the alarm, they are a frequent source of information for monitoring. Operators can also gain information from communication and logs about the plant to aid in their monitoring of the plant. Operators tended to communicate with other operators during shift turnovers in order to understand the status of the plant and any situations that they need to be aware of. Operators in the control room also communicated with other operators located in the plant during their shift to obtain information about certain systems and equipment. Historical information documented in logs and longer-term status binders tend to be used as reminders to the operators of what has been done in the previous shifts or in the past several weeks. In addition, operators also utilized plant walk-throughs as a means of providing a background, or context, for monitoring [13].

Challenges

Because of the age of some nuclear power plants, the systems that are used for monitoring can be unreliable. In [13], researchers found there was always components, instruments, or subsystems that are missing, broken, working imperfectly, or being worked on. This changes the way that the operators interpret the information from the system because they have difficulty establishing what is normal and correct due to unreliable sensors. This is further exacerbated by the fact that systems are complex and interrelated, which makes it difficult to understand the implications of failures.

The alarm system also poses a challenge. The alarm system produces alarms that are not context sensitive leading to many nuisance alarms. For instance, the same alarm may appear if a certain component is being repaired or if a certain component is not working correctly (Byzantine errors). Due to many false positives, operators may spend an inordinate amount of time filtering alarms [13].

The display design is another challenge. Operators must monitor a display of instruments serially remembering positions and values. Typical displays are cluttered and difficult to read because the instruments are so closely packed and the indicator and its proximity to the set point are difficult to read from a distance [13]. It is difficult to derive higher-order status from low level instrument data such that diagnosis of the nature of abnormalities is problematic [15].

Stress can have an adverse effect on operator performance. The stress placed on an operator could be the result of workload, competing goals, uncertain conditions, and other factors that can contribute to a loss of control. During high stress situations, performance on tasks that require integration of many cues or decision making that requires consideration of many options may be impaired because of decreased ability to allocate attention to peripheral cues. Furthermore, stress can result in a failure of work teams to pool information, thereby jeopardizing effective situational assessment [16].

Proposed Solutions

In the case study presented in [13], researchers found that operators were better able to perform their duties by adapting with new strategies to help their monitoring task. For instance, operators maximized the information that could be extracted from data through experience with the system. Operators also used the equipment to create new information by creating a new indicator or alarm. Moreover, operators could create external cues as reminders [13].

Information can be better presented to operators. One area of research has focused on how to integrate low-level data into high-level information that an operator can more easily process and understand [14]. In this way, operators can monitor for functional goals rather than sensor level values [14]. This integration can also reduce the amount of data that an operator needs to monitor by having the system automate the task of collecting and structuring the data for the operator [14]. This is not to say that displays in the control room be eliminated, but that there should be a display that allows operators to see the status of the plant on a high-level through the integration of data. If there is a problem, the operators can then look at the specific values which might be the cause of the abnormalities or errors.

With the alarm system display, the alarms can be made to be more context sensitive. The system might be designed such that operators are allowed to customize what messages are displayed so that the number of nuisance alarms is minimized; thus, the amount of filtering that an operator needs to perform is reduced.

IV. ANALYSIS OF NETWORK MONITORING TASKS

The networks we have studied are monitored by human operators because humans are able to creatively handle new situations that will inevitably arise. In order to be effective in this way, human operators require a situational understanding of the network which is increasingly difficult as systems become more opaque, more complex, and interdependent [17]. While most network monitoring tasks can be characterized as normal day-to-day activities, when problems do arise operators then need to perform some combination of the following tasks: cue interpretation, hypothesis generation, hypothesis selection, and action selection [18]. We found in the networks we studied that using visualization for network monitoring is the primary means for supporting humans with these requirements by providing situational awareness, quick gathering of information [18], and a means to convey uncertainty to the decision-maker [19].

TABLE I COMPARISON OF CHALLENGES IN NETWORK MONITORING TASKS

	Network	Visualization	Interactive Capability
Proactive	air traffic	radar displays, visual contact	voice communication
	power grid	tables, text, maps	voice communication, physical inspection
	water system	gauge indicators	gathering data on-site
Reactive	nuclear plant	gauge indicators	physical inspection

A. *Challenges of monitoring*

In conducting the survey, we discovered common themes in the challenges that operators face when monitoring a complex network:

- *Experiencing data overload*. We found that operators can be overwhelmed with the amount of information that they need to monitor [5-8, 10, 13]. Visualization was the most effective technique for representing data in order to reduce this overload.

- *Difficulty in filtering data*. With the large amounts of data available to operators, operators can potentially spend a majority of their time sifting through data in order to find data that will add to their knowledge of the state of the network [13].

- *Querying for information about the network*. Operators can have difficulty in obtaining the data that they need in the form that they need. For example, operators may need an overview of the state of the network, but only low-level information (i.e. sensor data) is available; thus, operators may have difficulty in assessing the current state of the network [2].

- *Human operators respond to network management tasks along a continuum between proactive and reactive*. In proactive monitoring, operators seek to determine the current system state and then predict the trajectory of the future state of the network. This is most prominently seen with air traffic controllers that need to predict the trajectory of airplanes to prevent congestion or collisions [10]. In reactive monitoring, operators do not attempt to assess the future state of the network, but rather only react to alarms that explicitly define specific problems and then follow an official protocol to address these problems [6].

Table I represents these challenges based upon the type of monitoring performed by the operator as well as by common attributes of the monitoring task– data visualization and interactive query capability for information about the network.

We found that information about the network is presented in various formats to the human operators (visual, numerical, verbal, tactile) in the different networks we studied. Research results confirm our intuition that visual communication is more effective than either numerical or verbal communication for most environments [20, 21]. Comparing visual versus verbal/auditory or tactile presentation of data, empirical evidence shows that visual communications is more effective [22]. Within visual communications, using spatial cues is generally more effective than using only color cues [21]. Visually labeling elements with legend information in close proximity minimizes cognitive context switching but is not always observed in practice (the proximity compatibility principle) [23].

Operator decision-making in the network environments we studied is deeply involved with handling uncertainty. Often operator must judge best/expected/worst case outcomes based on uncertain inputs resulting in conservative risk-averse decision-making as the standard codified in procedures. Counter-intuitive results from [24-26] report that communicating uncertainty to operators has little or no effect on decision-making – these results may support reducing the required amount of information presented to operators for them to make decisions (eliminating the requirement for communicating uncertainty). It is important, however, to visually display data resolution and uncertainty. Empirical results also show that representing levels of resolution in three (or four) levels (such as danger, uncertain, safe) as opposed to just two levels (danger, safe) fosters greater human trust in systems by reducing false negative and false positive errors [27].

In times of high stress, human operators severely filter information by limiting their focus to a small subset of their normal observation in order to minimize cognitive load. At these times of high stress presenting less probabilistic information is preferable since the information display can induce specific behavior. Much more research is needed to analyze human operator decision-making in handling stress and processing uncertain data.

V. SUMMARY

We have surveyed four well-established and critically important networks which are monitored by human operators. Because generalizing about human monitoring is hard for even a single type of network, generalizing human monitoring across different types of networks is even more challenging. Despite this difficulty, there are a few generalizations that can be made from our literature survey: (1) visualization is primary way to communicate complex network information to human operators and it is either already in use or being designed for use in all of the networks we studied, (2) while the specific definition of situational awareness varies in meaning for different network types, the need to be aware of current status and its relation to potential future states was found in every network we studied, (3) human operator tasks fall into two major categories for the different networks we studied - proactive versus reactive network monitoring, and (4) since human operators have a need to both communicate with other humans and query automation for specific information, each network we studied supported some type of interactive capability appropriate for environment. Thus we posit that the combination of (1) visualization, (2) situational awareness, (3) proactive/reactive network monitoring, and (4) interactive capabilities are the four core elements necessary for effective human monitoring of complex networks.

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References

[1] W. Dawsey, "Personal Communications" Ph.D. student at University of Illinois Urbana-Illinois (discussing water plant monitoring), January/February 2005.

[2] E. Fontenot, P. Ingeduld, and D. Wood, "Real Time Analysis of Water Supply and Water Distribution Systems," *World Water and Environmental Resources Congress and Related Symposia*, 2003.

[3] A. Ostfeld and E. Salomons, "An Early Warning Detection System (EWDS) for Drinking Water Distribution Systems Security," *World Water and Environmental Resources Congress and Related Symposia*, 2003.

[4] A. Ostfeld and E. Salomons, "Optimal Layout of Early Warning Detection Stations for Water Distribution Systems Security," *Journal of Water Resource Planning and Management*, 2004.

[5] T. Overbye, D. Wiegmann, A. Rich, and Y. Sun, "Human Factors Aspects of Power System Voltage Contour Visualizations," *IEEE Transactions on Power Systems*, 2002.

[6] T. Overbye, Y. Sun, D. Wiegmann, and A. Rich, "Human Factors Aspects of Power System Visualizations: An Empirical Investigation," *Electric Power Components and Systems*, 2002.

[7] R. Klump, W. Wu, and G. Dooley, "Displaying Aggregate Data, Interrelated Quantities, and Data Trends in Electric Power Systems," *Hawaii International Conference on System Sciences*, 2003.

[8] G. d. Azevedo and C. d. Souza, "Enhancing the Human-Computer Interface of Power System Applications," *IEEE Transactions on Power Systems,* 1996.

[9] R. Christie, "Towards a Higher Level of User Interaction in the Energy Management Task," *IEEE International Conference on Humans, Information, and Technology*, 1994.

[10] C. D. Wickens, A. S. Mayor, and J. P. McGee, *Flight to the Future Human Factors in Air Traffic Control*. National Academy Press, 1997.

[11] R. W. Remington, J. C. Johnston, E. Ruthruff, M. Gold, and M. Romera, "Visual Search in Complex Displays: Factors Affecting Conflict Detection by Air Traffic Controllers," *Human Factors*, 2000, pp. 349-366.

[12] J. C. Johnston, K. Horlitz, and R. Edmiston, "Improving Situation Awareness Displays for Air Traffic Controllers," *7th International Symposium on Aviation Psychology*, 1993.

[13] R. Mumaw, E. Roth, K. Vicente, and C. Burns, "There is More to Monitoring a Nuclear Power Plant than Meets the Eye," *Human Factors and Ergonomics Society*, 2000, pp. 36-55.

[14] L. Beltracchi, "Energy, Mass, Model-Based Displays, and Memory Recall," *IEEE Transactions on Nuclear Science*, 1989.

[15] K. Vicente, N. Moray, J. Lee, J. Rasmussen, B. Jones, R. Brock, and T. Djemil, "Evaluation of a Rankine Cycle Display for Nuclear Power Plant Monitoring and Diagnosis," *Human Factors*, 1996, pp. 506-521.

[16] D. Desaulniers, "Stress in the Control Room: Effects and Solutions," *IEEE 6th Annual Human Factors Meeting*, 1997.

[17] J. Reason, *Human Error*. Cambridge University Press, 1990.

[18] N. Sarter and B. Schroeder, "Supporting Decision Making and Action Selection under Time Pressure and Uncertainty: The Case of In-Flight Icing," *Human Factors*, Vol. 43, 2001, pp. 573-583.

[19] R. Finger and A. M. Bisantz, "Utilizing Graphical Formats to Convey Uncertainty in a Decision-making Task," *Theoretical Issues in Ergonomics Science*, vol. 3, 2002, pp. 1-25.

[20] S. S. Kirschenbaum and J. E. Arruda, "Effects of Graphic and Verbal Probability Information on Command Decision-Making," *Human Factors*, Vol. 36, 1994, pp. 406-418.

[21] A. D. Andre and H. A. Cutler, "Displaying Uncertainty in Advanced Navigation Systems," *Human Factors and Ergonomics Society 42nd Annual Meeting*, 1998.

[22] S. Basapur, A. M. Bisantz, and T. Kesavadas, "The Effect of Display Modality on Decision-Making with Uncertainty," *Human Factors and Ergonomics Society Annual Meeting*, 2004.

[23] C. D. Wickens, "The Proximity Compatibility Principle: Its Psychological Foundation and Its Relevance to Display Design," *Human Factors*, Vol. 37, 1995, pp. 473-494.

[24] C. D. Wickens, K. Gempler, and M. E. Morphew, "Workload and Reliability of Predictor Displays in Aircraft Traffic Avoidance," *Transportation Human Factors Journal*, Vol. 2, 2000, pp. 99-126.

[25] M. Yeh, J. L. Merlo, C. D. Wickens, and D. L. Brandenburg, "Heads Up Versus Heads Down: The Costs of Imprecision, Unreliability, and Visual Clutter on Cue Effectiveness for Display Signaling"," *Human Factors*, Vol. 45, 2003, pp. 390-407.

[26] M. Smith and C. D. Wickens, "The Effects of

Display Highlighting and Event History on Operator Decision Making in a National Missile Defense System Application," *University of Illinois Technical Report ARL-99-7/FED-LAB-99-4*, 1999.

[27] R. D. Sorkin, B. H. Kantowitz, and S. C. Kantowitz, "Likelihood Alarm Displays," *Human Factors*, Vol. 30, 1988, pp. 445-459.