Perceptional Approach to Design of Industrial Plant Monitoring Systems

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Abstract— **In this paper, we have investigated the perceptional attitudes of a massive scale industrial plant staff towards process monitoring systems and focused on human factors that are influential in design of plant monitoring systems. The study is a part of a plant-wide monitoring system which is under development, aimed to help staff to monitor processes and plant performance in detail. The paper first gives focused introduction on large scale enterprise and plant monitoring and management information systems, then discusses human machine interaction relevance of these systems to the staff performance and perception. Examples from the literature and previous work are presented. Primary human factors in proactive monitoring and highly automated systems are briefly discussed. A design survey study follows the introduction and relevant literature sections. The survey is designed to collect perceptional status of the staff against such systems, including the perception of their current performance. Results are analyzed and discussed in order to enhance system design decisions in such plant monitoring systems. We believe that such perceptual studies, performed before attempting to implement large scale monitoring systems that are highly interactive to the existing staff, should be considered as essential part of the design process. The results of this study is being used as inputs in implementation of a recent petroleum plant monitoring system.**

Keywords-Plant Monitoring Systems; Management Information System; Perception, Human Performance.

I. INTRODUCTION

Large scale industrial plants comprise challenging environments for information technology specialists and software developers. Small scale plants do usually include few number of independent technical systems and simple information architecture. On the contrary, large scale plants are made up of various subsystems each probably built by different vendors at different times, using various technologies and diverse information architectures. Large scale plants are therefore significantly heterogeneous environments. Since assimilation of plant-wide information and trends completely by each user/staff is relatively a hard task in such heterogeneous environments, any lack of awareness about certain parameters could result in serious consequences and losses.

Modern process control systems are highly connected to plant-wide information systems and able to push significantly detailed data to upper information layers for control and monitoring activities. Such plants have highly automated processes with independent computerized process controllers that are responsible for running individual processes in optimum performance. High degree of automation and heterogeneous structure usually impairs visibility of parametric information about processes.

Often, information exchange between these automation and users who are responsible from running the plant are inadequate. This can eventually cause inefficiencies in plant performance and even result in life threatening catastrophes. The famous Three Mile Island nuclear accident (1979), is one example where poor user-system information exchange caused catastrophic plant failure [1][2].

Munro and Tilyard indicate the problem of user interaction in industrial environments as follows: “The industry’s strength has been in finding technical or hardware solutions while its weakness has been at the people end of the business in maximizing and consolidating the gains from the technologies” [3].

Monitoring a complex system is generally a hard task. A human operator needs to be aware of what is going on in a plant to a certain degree where his job is performed without any consequences or loss of production. However, required degree of awareness and level of detail that need to be provided remain unknown for most cases. The term “situational awareness” is used to describe this condition in literature. There have been numerous studies regarding situational awareness of the user in aviation and military areas due to their relative importance due to life critical nature of the operations [4][5]. As plant technologies advance, importance of plant monitoring also becoming significant both due to increased life critical nature and economical impacts in case of possible failures. When plant staff is unable to interact with and control correctly the required parameters, it is usually attributed to situational awareness problem. This is due to the fact that a normal behaving staff would think to act positively and in parallel to task descriptions in all situations.

Researcher David Hopkins summarizes major reasons of most situational awareness problems into four categories in terms of their consequences on user actions [6]:

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1. The user has a full appreciation and understanding of the situation but an inability to take action. This is rare but may occur, such as, in extreme fatigue where the human can appreciate a situation but is too tired to do anything about it.

2. The user may have an adequate perception of all the relevant stimuli but a failure to appreciate their meaning or import. For example, the user may see an indicator, but forget what it means.

3. A user may fail to perceive a particular stimulus. He/she may not notice an icon for example, but see other items perfectly well.

4. A user may not perceive any of the surrounding stimuli, being for example, preoccupied with his/her thoughts and mind wandering.

Among the above problems the first one is rarely observed in extreme circumstances in critical conditions. Job descriptions, workflow and management decisions are expected to eliminate such scenarios. However, latter three are highly relevant to system design, information presentation, user interaction design and interruption mechanisms. It is therefore essential to establish a successful system-operator interaction with adequate and reliable information flow for a highly complex industrial plant.

An important fact of most industrial plants is that large amounts of staff work together. Some of them work in shifts whereas other work during day work hours. Therefore a collaborative awareness about plant is sought. This type of awareness about the status of the plant processes can be interrupted or totally lost, due to multiple causes such as lack of adequate collaboration or improper handover structure between shifts [7]. These problems can further be worsened through inadequate and mismanaged flow of information to user from the plant, unavailability of temporal and historical information from system monitoring displays and other factors.

It is therefore imperative for a good plant monitoring architecture, to be designed in accordance with expectations and needs of the staff and theoretical foundations of human machine interaction discipline.

The remainder of this paper is organized as follows. In Section 2 we discuss relevant properties of plant monitoring systems. Section 4 gives the results of the survey study which is given in Section 3. We provide results and discussion in Section 4 and Section 5 respectively. Conclusive remarks are given in Section 6.

II. PLANT MONITORING SYSTEMS

Complex industrial plants have numerous activities and processes that are independent of each other while being controlled by an army of staff and workers, where some work at different hours. Although these processes are independent processes and controlled by independent automation and staff, they are also interrelated through product flow, energy and other variables to some degree [8]. Therefore, upper level supervisory monitoring and control, focusing on the whole plant as a single entity is also a necessity. Typical staff types that are in touch with plant monitoring activities are as follows:

- Facility operation engineers, engineers, specialists
- Unit head operators, and unit operators
- Unit and facility operation chiefs, chiefs
- Unit and facility chief engineers, chief engineers, coordinators
- Managers and upper level staff

Considering needs of above different staff members of a plant, a hierarchical multiple level architecture for monitoring and control is necessary as shown in Figure 1.

Due to massive number of plant variables and separated units which are often installed by different vendors at different times, large scale industrial plants have at least four different monitoring levels about ongoing operations. At each level, as one moves up, level of detail is reduced and plant-wide abstraction with data combination is performed. This enables strategic thinking and better management decision making. On the other hand, monitoring tasks at lower levels require more fine grained, localized parametric access, visualization and control.

When an individual process of a plant is concerned, process level monitoring is implemented and staff is only trained and responsible from monitoring only the process that he/she is assigned to. Similarly, middle level engineers, unit chiefs, operation engineers are more interested in examining and monitoring the conditions of units that they are responsible for as a complete set. Upper management on the other hand, mush have access to all parameters in more abstract forms but only in detail when required. Moreover, security and authorization mechanisms must be implemented between different levels and members of all plant monitoring staff.

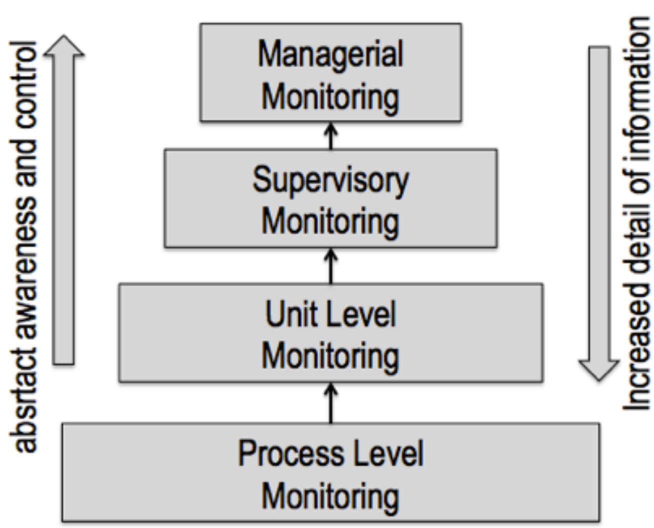

Figure 1. Multiple levels of monitoring in large scale plants.

For safety and successful integration, supervisory monitor level is placed at a level where chief engineers monitor individual units, processes or overall of the plant. At the top, managerial monitoring for decision process and implementation is required to steer the plant with respect to business goals and market conditions, such as accommodation to market conditions and adaptation to input supply levels. Therefore as greater overall control power is expected in managerial level of monitoring, lower details should be visible in order to enable situational awareness of the whole plant variables.

Unlike systems of 1990's or earlier, today's plant control computers are highly connected through plant-wide networks. These are usually number of individual networks such as separate ones for data collection, control and security operations. Typical components of large scale plant information system is shown in Figure 2. Vast number of sensors connected to individual machines, reactors, motors etc. allows plant engineers to collect valuable information remotely through plant-wide information network. However, this benefit poses three challenges:

a) Storing sensor and status data in a central database,
b) Using various collected data for information extraction and automation purposes,
c) Representation and visualization of this data for human consumption, monitoring and decision making.

Therefore, contemporary plant monitoring and control systems with data collection and storage facilities are required in order to keep up with this new kind of high volume data. Furthermore, presentation of such a high volume data in a proper way, so that it can be assimilated and used for decision making by different staff is a challenging task. A "user centric" plant monitoring and control strategy needs to be implemented to achieve high situational awareness about the current and historical status of the plant condition. The following section further discusses stages of plant monitoring and critical components in order to create a user centered modern plant monitoring system.

A. *Several Stages of Monitoring*

Li et. al in their study, suggests to study monitoring process in four stages [9]. These are briefly described as follows:

Detection: The first stage, detection, involves sensing, perception and discrimination of the current state of the process. Thus, early and accurate detection is critical to any successful human intervention. Existing research suggests that 30% of the human error failures occurred at the detection stage [10].

Analysis: The second stage is quite a complicated cognitive process. It usually involves interpreting current process state, reasoning possible causes of any unusual condition, projecting the future process state with or without a specific intervention, planning future actions or assessing the associated risks and competing prioritization of control tasks. These activities require adequate operational knowledge and experience. The research indicate that most operators mainly rely on trend displays, data overview displays and CCTV (Close-Circuit Television) to analyze process status.

Action: This step involves conducting necessary actions in order to meet predetermined goals of plant production based on the cognitive analysis of the data that is assimilated in previous stage.

Evaluation: The last stage, evaluation, basically determines whether the process has been stabilized or not by monitoring the feedback from control system. An operator needs to know what the current process state is, and whether it is moving in the right direction towards production goals, and when he/she can return control to automation if it exists. Usually, operators would target same displays and control system screens used at analysis stage for this evaluation task. There are several factors associated with these stages that may cause incorrect handling of plant operations among these the following can be given as major ones:

"Alarm Flooding" with too many alarms causing ignorance of alarms. Failure to mentally integrate distributed information on screens. Low trust in sensor readings and lack of early detection support on the interface and underlying technology. Lack of in-depth insight of critical process dynamics and lack of predication of future plant state [11]. As a result of above factors, an operator may fall into a situation where overall mental picture of process performance is absent.

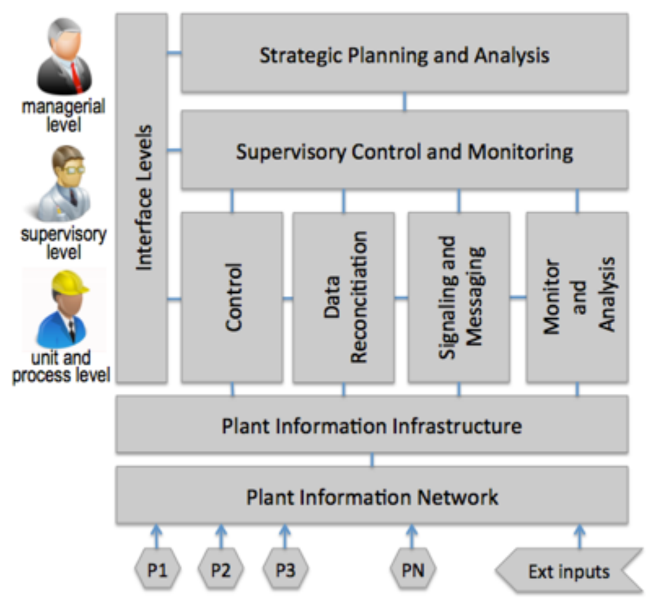

Figure 2. Primary monitoring components of large scale plant management information system.

B. *Proactive Monitoring*

Proactive monitoring is the term that describes monitoring paradigm, that enables operators to take actions

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before unwanted events occur. Through monitoring proactively, it is hoped that staff would notice problems while they are visible as small events, and can intervene before there are more drastic consequences, such as larger equipment failures, plant destabilization, human injury or loss of production efficiency [12].

A significant portion of proactive monitoring lies under “trend monitoring” and “trend analysis” techniques [13]. Reacting proactively means taking a more comprehensive look at human factors in order to sustain efficient and safe operation of a plant. Trend monitoring techniques rely on collection of significant amount of data and displaying current values along with and with respect to old values indicating trends to human operator [14][15]. Proactive monitoring therefore requires high situational awareness and understanding facts about a plant or unit in which a human monitoring staff is responsible. In order to provide this, such responsible staff should be able to ascertain,

- “What is the system doing now?”
- “Why is it doing that it is doing?”
- “What will it do in near future?”

We believe that well designed human machine interfaces along with adequately trained staff regarding underlying structure of the processes can achieve above three requirements. However, as systems include more automation behind controllers, the problem of “automation opacity” becomes an issue affecting awareness of control/monitor staff about current status of the processes. Abstraction techniques that incorporate and reflect principles of underlying automation (controller behavior) used for such processes, can help to overcome opacity issues and increase proactive monitoring success. Care must be taken when designing interfaces for these systems without obscuring underlying structure and creating false cognitive mental models. The survey study that is explained in Section 3 attempts to gather preliminary information on how information technology and graphical user interfaces can work together helping to achieve better level of proactive plant monitoring.

C. *Information Flow and Messaging*

Large industrial plants have number of people working together, sometimes on the same unit, plant, process and sometimes on different ones. Although most are relatively independent, there are sometimes relations between parameters where one staff is responsible from and other is not in particular. In such cases, monitoring staff usually inform each other via various different information channels. Common methods are calling via telephone, sending e-mail or SMS message, sending paper message or sometimes visiting in person.

Therefore, a contemporary plant monitoring system is necessary, enabling staff interaction through advanced messaging and notification mechanisms. This, in turn will help reduce overhead and redundant messaging and interactions through traditional channels, as well as possible errors. Further, a successful notification system will have learning capabilities, in such a way that certain types of events are automatically routed to responsible monitoring staff once they are initially addressed as a result of manual notification by peers. Messaging and notification architecture should allow labeling certain normal and abnormal cases for further notification processing.

It is also noteworthy to mention that temporal status of the plant units and processes should be carried through between shifts. As mentioned in earlier sections, using advanced trend analysis, display techniques and user message tagging to the trend display data, monitoring staff can have access to all information beyond their allocated time span during their work time.

III. SURVEY STUDY

Based on the literature that we have reviewed, it was found necessary to conduct a preliminary survey study, understanding what staff thinks about current and future monitoring structure. It was planned to make a survey study and then, to use the outcomes in design of the new plant-wide management information and plant monitoring system.

We have conducted a survey study prior designing the plant-wide monitoring for management information systems among the related staff. Based on the previous research, it was essential for the staff to accept the technology and methods in order to fully utilize in the work environment. 22 subjects selected randomly from petroleum plant staff working in various positions (except worker level) related to monitoring tasks are selected. They were interviewed and given a questionnaire regarding the plant-wide monitoring system. Both quantitative and qualitative results are obtained as an input to design of monitoring system.

A. *Questionnaire*

A total of 20 question questionnaire with an addition of open ended free discussion form was given to oil refinery staff. Questions were targeted to understand the attitude and perception of staff towards proactive and enhanced plant monitoring and management information system. Open ended and explanatory questions were also asked in order to gather as much information as possible. Main focus of the questionnaire was to identify how much staff time and effort was currently allocated to plant monitoring tasks and how difficult is to work with the existing structure. Understanding and attitude of staff perception towards plant monitoring were key issues in answering these questions.

The effect of possible new information architecture and staff perception towards this was among expected outcomes of the study. Furthermore, crucial parameters, the expected frequency of monitoring these parameters and additional information to understand daily activities of staff were asked as questions in the study. Prior to giving the questionnaire, full confidentiality were assured, and the purpose of the study was explained.

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IV. RESULTS

Tabular results that were obtained from the questionnaires given in Table 1 and Table 2. In terms of a measure for engagement to monitoring activities, subjects indicated that they spend over 75% of their overall work time using computers where 17% of this time (mean value) is dedicated to monitoring activities. 22 parameters must be continuously monitored on average and 16 parameters must be checked daily. Higher number of parameters however (64) must be checked occasionally although variance between subjects was high on that parameter.

TABLE I. CATEGORICAL QUESTIONS REGARDING MONITORING TASKS

No	Question	mean (std) (median)
1	How often you look at the parameter that you are mostly interested in?	3.09 (0,68) (3)
2	Do you think you or other staff made errors in the past in monitoring refinery parameters?	4.35 (0,89) (4)
3	Do you think you spend too much time with software and methods in monitoring parameters?	3.75 (1,26) (4)
4	Do you think there are measurement devices in operation that have errors beyond acceptable limits?	4.55 (0,93) (5)
5	Do you prefer the variables that you follow be represented in graphical formats such as bar charts, pie charts, histograms etc?	4,61 (0,74) (5)
6	Do you believe that graphical representation is not as necessary and you can monitor parameters by looking at numbers?	1,55 (0,83) (1,5)
7	Do you share refinery parameter facts that pulls your attention with your colleagues other than your manager?	4,47 (0,77) (4)
8	Do you need printed material when making decisions regarding plant parameters?	2,69 (1,25) (3)
9	Do you think that better use of information technologies will improve refinery efficiency?	4,75 (0,66) (5)
10	Do you think is it technically beneficial to be able to check parameters that you are responsible by using mobile phone?	4,47 (0,70) (4)
11	Do you think that you know refinery processes well enough?	3,87 (1,21) (4)

Answers for 5-point likert scale (strongly disagree, disagree, neutral, agree, strongly Agree) questions indicated a clear positive attitude towards graphical plant monitoring systems and their benefits. Subjects believed that they or other colleagues made errors in monitoring tasks in the past (4,35). They also believe that measurement devices in the plant might have inaccurate readings (4,55), which is indeed reported in literature among causes of situational awareness problems.

They support the use of graphical content and use of mobile phones to monitor parameters will be beneficial along with more intelligent and proactive information presentation. Subjects felt comfortable with understanding the plant parameters and indicated that they rarely open up printed material in order to understand and solve issues. Open ended questions were related to individual parameters that they are mostly interested in and how they want them to be presented in detail. We have gathered quite helpful individual details, parameter conventions, ranges and suggestions from the survey and follow up interviews after filling the questionnaires. These are beyond the scope of this paper and will be included in the final design.

TABLE II. NUMERICAL QUESTIONS REGARDING MONITORING TASKS

No	Question	mean (std) (median)
1	What percent of your total time do you spend on computers in your job normally?	76 % (24) (90%)
2	What percent of your total computer usage time at work goes to monitoring refinery plant parameters only?	17 % (23) (7,5%)
3	How many plant parameters that you may want to follow continuously?	22 (38) (5)
4	How many plant parameters that you may look at once a day?	16 (24) (6)
5	How many plant parameters that you may look at occasionally?	64 (211) (6)

V. DISCUSSION

Modern plant control and monitoring systems are significantly different from systems of the past. With the help of new advanced information technologies, plant operators seem to have access to all parameters; yet, having access to all parameters causes information overload and failures. To make things worse, advanced process automation techniques that are implemented in modern process control systems may hide certain details from the operator inadvertently, causing automation opaqueness. Moreover, market pressure, environmental concerns and tighter profit margins push plants into operating ranges that

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are very narrow, which further makes controlling and monitoring more difficult and critical.

A contemporary solution to this should employ user centered design of plant monitoring. Traditional reactive approach should be replaced with proactive techniques. The use of mobile devices, tablets, standalone status displays are reported as beneficial. In order to proactively monitor the system, integration of task elements into a highly graphical and well designed interface, with messaging, notification and data reconciliation properties is suggested. Through this, monitoring staff can achieve higher level of situational awareness and work in parallel to the plant objectives.

There might be other critical dimensions regarding plant-wide monitoring and control in modern plants such as security and vulnerability to malicious software. It becomes extremely critical, when staff start using mobile devices, smartphones and other equipment to reach and control plant parameters. As traditional plant systems are not connected directly to internet and mobile devices and assume presence of certain physical access security, such modern access methods which might seem beneficial at first, require extreme security measures, which are beyond the scope of this paper.

VI. CONCLUSION

We conclude that as recent connectivity and information technology properties of large industrial plants make new types of plant-wide control and monitoring tasks possible, one needs to define how these tasks will be implemented successfully through modern interactive user interfaces and mobile technologies.

It appears that staff work shifts, hierarchical organization structure and common understanding of plant goals are among the essential factors that must be taken into account. We observed that in many situations considerable amount of time required to monitor certain parameters periodically. Therefore, parameter information that is graphical and easy to assimilate will be welcomed both in mobile and desktop settings by plant staff.

We believe that staff surveys, in large plants must be conducted prior to modification and new design of control and monitoring systems. Getting into contact and collecting feedback from plant staff during design stages were found beneficial and encouraging in many directions. We have recently used the results of this study in development of our new plant monitoring software. Initial feedback that we received about our new software were satisfactory. An evaluation of new software is also planned, after being used for about a year for further conclusions.

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