The Application of Project Control Techniques to Process Control: The Effect of Temporal Information on Human Monitoring Tasks

A. Parush, A. Shtub, and D. Shavit

Abstract: We studied the use of time-related information, with and without prediction, to support human operators performing monitoring and control tasks in the process. Based on monitoring and control techniques used for Project Management we developed a display design for the process industries. A simulated power plant was used to test the hypothesis that availability of predictions along with information on past trends can improve the performances of the human operator handling faults. Several designs of displays were tested in the experiment in which human operators had to detect and handle two types of faults (local and system wide) in the simulated electricity generation process. Analysis of the results revealed that temporal data, with and without prediction, significantly reduced response time. Our results encourage the integration of temporal information and prediction in displays used for the control processes to enhance the capabilities of the human operators. Based on the analysis we propose some guidelines for the designer of the human interface of a process control system.

Keywords: control systems, process control, temporal data, predictions, human computer interface

I. Process control displays

The need to monitor and control complex processes where many parameters interact with each other is well recognized. Examples exist in areas such as monitoring and control of patients in intensive care units, reactors in the process industries, power plants in the utilities industry, airplanes and spacecrafts in the space and aviation industries. A similar problem exists in projects where due to uncertainty, actual performances deviate from project plans and a continuous effort is required to keep the projects on track.

One of the key factors affecting a human operator's ability to control a complex system or a project is the operator's Situation Awareness (SA). Endesly (1995) suggested that this is the ability to understand information on the values of (measured) factors and to predict the effect of these factors on the system in the future.

There are several approaches to process control displays that can provide some situation awareness. A common approach is based on the single sensor, single indicator concept (Goodstein 1981). However, this approach causes a heavy cognitive load on the operator who has to read and integrate data from many sources. Research in this area led to the conclusion that it is important to present the data in a way that reduces the cognitive load. One solution is based on the mapping principle (Woods 1991), i.e., displaying the information on a graphical model (a map) of the process. Beltracchi (1987) and Vicente et al. (1996) applied the mapping principle to the Rankin Cycle (the process used to generate power in a power plant by steam-driven turbines). They found in their experiment that the application of the mapping principle reduced the number of mistakes made by the process operator significantly. Another commonly used approach to the design of process displays is based on the Rapid Serial Visual Presentation (RSVP) in which a set of digital displays on the control panel is used to present the relevant data (Endesly 1995). The Rapid Communication Display (RAP COM) includes a single display that presents multiple values as a function of time (Martin and Boff 1988). An important design parameter for both RSVP and RAP COM is the refreshing cycle time used to update the information on the screen. Since only current information is presented, optimal refreshing cycles should be used to support the user while minimizing the cognitive load (Konrad et al. 1996).

An example of information extraction is a centralized or object display, which is based on geometric templates. Thus for example Woods et al. (1981) suggested a single geometric display to present 100 sensors in a control room of a nuclear power plant. They suggested a polygon with a symmetrical geometry to represent a system in a normal state that changes to an asymmetrical geometry to represent a system state that requires operator intervention.

Among the graphical approaches used for display of control data, the parallel graphs or multidimensional lines (Inselberg 1994) is capable of displaying multiple sources of information simultaneously. The idea is to use multiple parallel axes, each representing a single parameter. Thus the inherent limitation of Cartesian systems (where the axes are orthogonal to each other) - the ability to present at most three parameters simultaneously disappears and any number of parameters can be displayed simultaneously.

II. The importance of temporal data display

The common principle in the above reviewed traditional display approaches is that the operator receives information about the current state of the system (e.g., the temperature of a car engine) or signals alerting him about a deviation from a preset value (e.g., a red light indicating an overheated engine). Based on this information, the operator has to decide if and how to react. However, this approach may not always provide sufficient information to support an operator's decision. In typical process control it may affect the ability to detect system failures and diagnose them appropriately. This is also the case, for example, in project management where cost, schedule and work content (or project scope) are typically used as control parameters. A deviation in any one of these parameters tends to affect the other two.

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To overcome this problem, integrated control systems are used where temporal information about several parameters is presented simultaneously with information about past trends. For example, Earned Value control systems for project management (see a discussion in Shtub et al. 1994) present information about past values of three control parameters: the Budgeted Cost of Work Scheduled (BCWS), Budgeted Cost of Work Performed (BCWP) and Actual Cost of Work Performed (ACWP). The simultaneous presentation of these values as a function of time is a common practice. Furthermore a forecast of future values of the project's cost and duration is usually presented to support decisions regarding managerial actions and the development of future plans for the project.

A similar approach is used in medical applications - by opening a moving time window that performs the display of past information. Thus the operator receives information on the current value of important parameters as well as the past values over the time window. The display is dynamic in the sense that the time window is moving and every time that new information is displayed the oldest information is removed from the system.

Data presentation, data integration and the presentation of data variation over time are three factors affecting the Situation Awareness of a human operator and the ability to control complex systems. An interesting unresolved issue is the effect of forecasts on operator performances. Problem solving requires not only the understanding of the current state of the system, but also an indication of the future state, in order to reduce the cognitive load on the operator and help him do a better job.

In this paper we focused on the design of displays for control systems. We particularly studied the use of temporal (or time related) information in such systems and its effect on the performances of the human operator. Specifically we added forecasts of future states of the system to support the human operator's decision-making process. We hypothesized that it is possible to improve the Situation Awareness of the operator by providing him with past information and a forecast of future values of individual factors, thus making it easier for him to understand the state of the system, detect failures early, and take the correct action.

To test our hypothesis we designed an experiment in which a power plant is simulated and controlled by the participating subjects. Several alternative control system designs were tested; some designs presented only current information while other presented past information or past information with forecasts.

III. The proposed model for temporal displays

A model of the Rankin process in a power plant was developed. Implementing the logic of a moving time window, presentation of information as a function of time requires two dimensions – the dimension of time and a dimension representing the monitored parameter. To achieve integration of all the parameters monitored, several two-dimensional parallel graphs were used. Each graph represented one parameter as a function of time. The time axis was divided into three: past information, the current value and future (forecasted) values. By using the same scale for time on all the parallel graphs, it was relatively easy to see the state of the system in any given point of time, as illustrated in Figure 1.

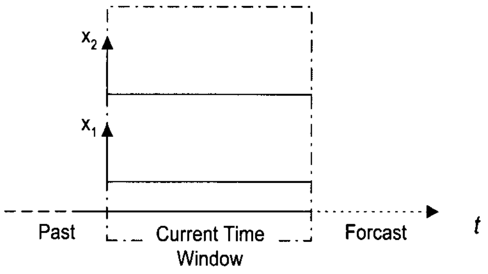


Fig. 1.

To forecast future values of a parameter a suitable forecasting technique was needed. The selection of a forecasting technique depends on the components of the time series representing specific parameter values. Thus if only trend and random components exist in the time series, a simple linear regression can be used. However, if seasonal cyclical or autocorrelation components exist as well, more sophisticated forecasting techniques such as triple exponential smoothing or Box Jenkins-type models may be adopted.

For the sake of simplicity we assumed that a random component and a trend dominate the time series modeled, and consequently selected regression analysis for forecasting. The display of information by parallel graphs with a common time axis, a moving time window and a forecast of future values of the parameters was implemented using the mapping principle on a diagram of the Rankin process.

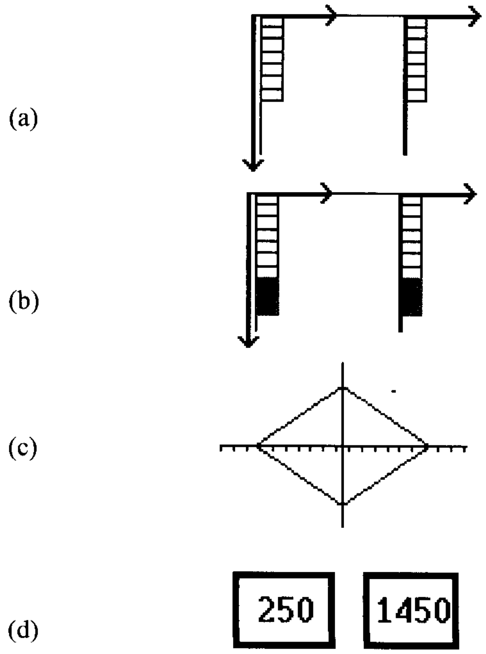


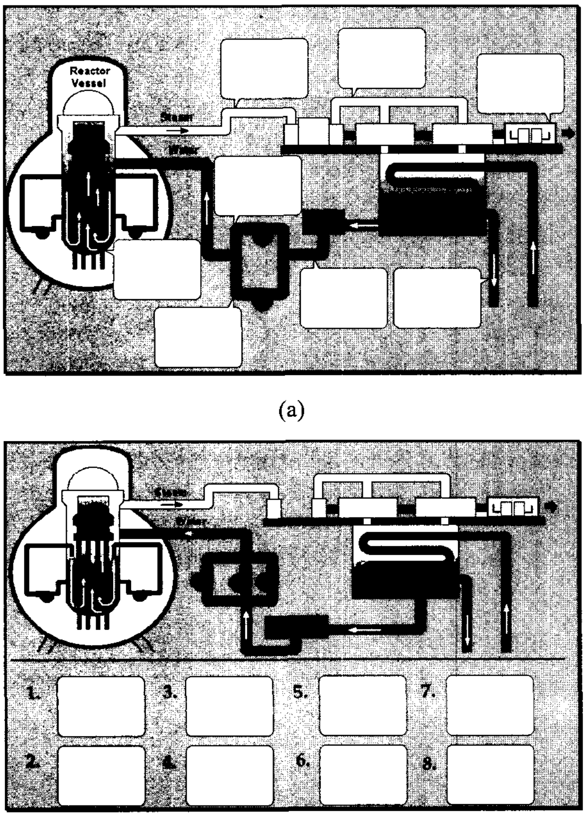
Fig. 2.

As a reference we also tested the performances of the operators using three other designs of displays (see figure 2):

- A parallel set of graphs that present past and current data on a common time scale without prediction (figure 2a)
- A parallel set of graphs that present past and current data on a common time scale with prediction (figure 2b)
- A polygon display where symmetry represents the problem - free state of the system (figure 2c).
- Digital display of the current values of the parameters (figure 2d).

To analyze the effect of the mapping principle each of the four displays was implemented twice (see figure 3):

- On a process diagram of the Rankin process (figure 3a).
- On a display that clusters the information on the screen without any reference to the process diagram (figure 3b).



(a)

(b)

Fig. 3.

Two types of faults were generated in the experiment – local problems that affected only part of the Rankin process, and system-wide problems that affected the whole process.

IV. Methodology

1. Experiment design and setup

A fully factorial 4x2x2 repeated-measures design was employed. The experimental design was based on three main factors:

1. Data display: 4 display types were tested - numeric, object, history, history + prediction.
2. Fault: 2 fault types were tested - local vs. global.
3. Mapping: 2 layouts were tested: data displays mapped, i.e., embedded within the process picture vs. data displays not mapped, i.e., external to the process picture.

Special software written for the experiment (in Visual Basic 5.0) generated the eight display combinations and a random sequence of problems.

2. Measurements

Monitoring performance was examined by two measurements:

Response time: Time from beginning of the fault to the time it was detected correctly.

Accuracy: The number of trials until the origin of the problem was detected correctly.

3. Subjects

Forty Industrial Engineering students participated as subjects in the experiment. All had no prior knowledge or experience in the operation and control task of power plants. Each of the forty subjects who participated in the experiment had to go through a sequence of displays and problem types and to take proper action according to the information presented by the system.

4. Procedure

A special training module that explained the purpose of the experiment and the Rankin process that the participants had to control was used to train the subjects. In the introduction the difference between a local fault that affected only part of the process and a global fault that affected the whole process was explained as well as the variety of display types used in the experiment. The participants also learned how to "solve" problems by either pointing with the mouse at the source of the problem or by keying in a number representing the problem source. Following the introduction each participant had to monitor the process for about seven minutes during which he had to identify and solve a sequence of problems presented to him. The response time as well as the number of mistakes made by each subject was recorded in a database that was analyzed offline.

V. Results

1. Response time

The mean response times (and the standard deviations) are presented in Table 1.

Table 1. Mean response times (along with the standard deviations) for all experimental design conditions.

			Data Display Type			
			Prediction Presented	Histor presented	Numerical Display	Polygon display
		Type of problem				
Mapping	With mapping	Global	4.935 (0.870)	5.660 (1.224)	6.260 (1.153)	6.812 (1.216)
		Local	4.494 (0.933)	5.002 (0.853)	5.834 (1.360)	5.726 (1.151)
	Without mapping	Global	4.743 (0.943)	5.558 (1.204)	5.857 (1.164)	6.244 (1.459)
		Local	4.434 (0.986)	4.915 (0.883)	4.907 (1.363)	5.010 (1.209)

Figure 4a shows the significant interaction between data display type and mapping (F=2.88, p<.05).

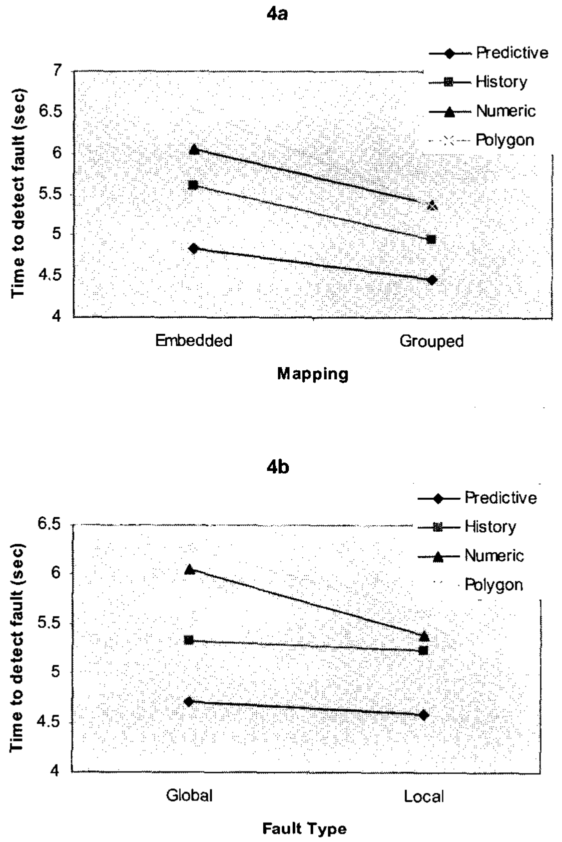


Fig. 4.

It can be seen that in general, response times for the temporal display with prediction were the shortest, followed by the response times for the temporal display without prediction. The response times for the object/polygon display were the longest. Response times for unmapped layouts were shorter, for all display types, as compared to mapped layouts. In addition, the differences in response times between the different display types were greater for the mapped layout.

Similar trends can be seen in figure 4b for the significant interaction between data display type and the fault type (F=3.45, p<.05).

2. Response accuracy

A similar analysis on the number of trials required to solve a problem revealed that all three main factors have a significant effect as well as the interaction between the problem type and the display type.

Figure 5 shows a significant interaction between fault type and display type (F=16.57, p<.01).

It can be seen that there were significant differences in the number of trials to solve a problem only for the global-type problem. The least number of trials was required for the polygon display, and the most number of trials for the numeric display. There were no differences between the two temporal display types.

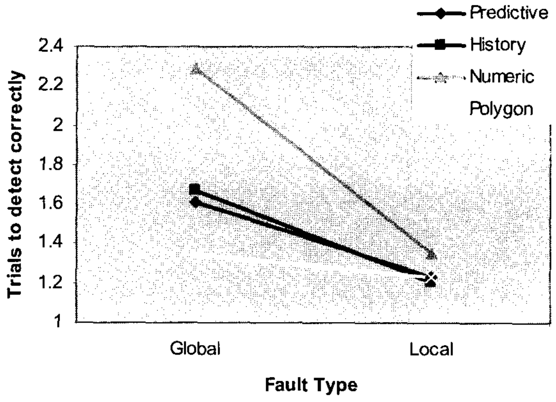


Fig. 5.

IV. Discussion

We tested the hypothesis that prediction in temporal display can improve the performances of the operator controlling complex systems. A simple comparison of response times reveals that forecasts reduced response time by up to 25%. It is important to note that historical information also reduced the response time relative to display types that did not contain such information, such as the object/polygon or numeric displays.

It is not immediately clear why the object display produced the longest response time, even when compared to the numeric display. It is possible that the nature of the monitoring task examined in this study affected the performance with this display. The requirement was to detect, as early as possible, the source of the fault. Since the detection was done partially based on the derived temporal pattern of the event and its dynamic development, the polygon display was less effective in conveying this specific type of information. It seems that the participants were able to derive that dynamic information better from the numeric display.

However, there was a clear speed-accuracy tradeoff concerning the polygon display. It was found that it required the least number of trials to detect the fault source. Since it took longer for the participant to detect the source they had "more time" to detect it correctly with less trials. More trials were required for all other display types indicating the speed-accuracy tradeoff in the opposite direction.

The results of our study suggest that when the data displays are not mapped to the representation of the process it produces shorter response times. This finding is not consistent with other findings, such as Vicente et al. (1996) who suggested that mapping does improve response accuracy. It should be noted that in our study there was a significant interaction between display type and mapping in their effect on response time, but no such interaction was found with regards to the accuracy index (number of trials to detect the source of a problem). Thus, the primary effect of the mapping factor on response times can be related to the less complex visual scanning patterns that participants performed in order to detect the fault in the layout where all displays were concentrated in a single area (not mapped). Such a result can support a design recommendation for system and process control requiring immediate response, even at the expense of accuracy. Life-critical situations, such as medical or military, may require such a monitoring behavior. For example, in the aircraft cockpit in which an immediate response is required, there is usually a concentration of all major warning indicators in a single location, regardless of the actual location of the warning source (no mapping).

Situational Awareness (SA) is an important factor affecting the ability of the human operator to react correctly and in a short response time to the signals produced by a control system. The experiment performed in this study shows that a significant improvement in the operator's response time is possible when temporal information is provided, and in particular when prediction of future values of the controlled parameters are presented. The display design as well as the content of the displayed information emerged as important factors that should be taken into consideration in the design of control systems.

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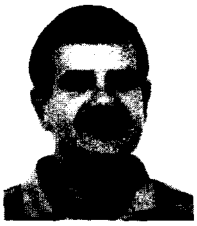

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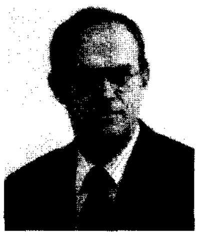

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