Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Benefit and evaluation of interactive 3D process data visualization in operator training of plant manufacturing industry

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***Abstract*— Operator training without a process model is necessary in certain plant manufacturing industry's applications because the process models from the control theory perspective are still not available. This paper describes an experiment that analyzed the benefits of 3D data visualization integrated in HMI for process control in combination with different types of operator training to obtain process knowledge. The benefits of interactive 3D slider training in identifying errors during operation could be proven.**

***Keywords*—3D prozess data visualization, operator training**

I. INTRODUCTION

The increasing complexity of industrial plants leads to a growing amount of process information that has to be monitored and controlled by the operators. Centralized control rooms and the reduction of operator personal force the operator's workload additionally. This results in an increasing probability of operator errors.

Nowadays 2D-representations, like bar graphs, line-diagrams and tables are common in process data visualization in Human Machine Interface (HMI). With the growing amount of information, these conventional types of visualization reach their limits and process visualization gets more and more confusing and this impair fast error detection. From the plant operators' and plant manufacturers' point of view the operator needs better support. One of the main questions is: What can be done to support the operator in his special task to observe the process?

The first possibility is to reduce the complexity of HMI by integrating process data representations. With a 3D visualization it is possible to integrate more information in the visualization. The third dimension of a chart can be used to represent spatial or chronological information. Additionally, the information content of the visualization can be increased by coding the data, e.g. through color or surface design. By means of coloring and surface design it is possible to show more data in one view and to visualize potential coherences.

3D diagrams are the state of the art in data analysis. Programs like MATLAB or Excel already use 3D visualization for diagrams in a simple way. However, these diagrams are rarely used in process control. The time consuming development process could be a reason for this. In previous works we developed a library with 3D diagram objects as a prototype, so called pattern that can be used in different SCADA Systems [1]. These 3D patterns may be integrated via standard interfaces like ActiveX or OPC and can be implemented from a library in the same way as 2D diagrams.

The second possibility is to support the operator in developing process knowledge during the training phase in a more appropriate way. Usually this is done by model based process simulation (control model). For some industrial process [2], [3] it is difficult and time consuming to identify a suitable model and therefore none has been successfully developed. Alternatively, an operator training system may be based on recorded process data. In our opinion it could be very helpful to train the operator with a data player, a so called slider, displaying continuous historical data flows. With the functionality of the slider it is possible to analyze historical data in an adjustable temporal scaling. This will support the operator in analyzing and learning the dynamic behavior of a process in critical situations and to use the gained knowledge later during operation of the plant.

This paper describes an experiment that analyzed the benefits of 3D data visualization as part of an HMI in combination with different types of operator training in process control.

II. MULTIDIMENSIONAL PROCESS VISUALIZATION

A. State of the art

2D visualization is state of the art to display process data in an HMI. Classical HMI applications allow designing process images in 2D and connecting it with the process values in a simple way. In some applications, e.g. tanks or piping are represented in 3D but from the operators' point of view, there is no additional benefit generated by this kind of 3D visualization. Even though 3D visualization is often considered as gimmick, there are different studies that show the benefits of 3D in process control. During the identification of system status Beuthel [4] and Hoppe [5] proved the advantages of integrating 3D process visualizations for the application of a coal-fired power plant and electric power grit. Both studies measured the reaction time and the processing time to handle the problems presented in 2D as compared with 3D visualization. The results showed an advantage for 3D visualization.

In previous experiments the authors already evaluated 2D and 3D visualization in HMI for one industrial application [6]. 3D visualization showed significant faster reaction times if problems are complex enough.

However, in the pilot test only one out of five problem situations showed this benefit. One reason could be the reduced complexity of the experimental environment as compared with real tasks. The subjects only have to observe one diagram and could concentrate completely on this task. In contrast, an operator in a real control room is confronted with different additional tasks that distract him from the main task and by that reduces his attention when monitoring the process. This result is consistent with Wickens' "Proximity-Compatibility"-principle [7]. This principle states that tasks, that require the integration of information benefit from a perceptual proximity of the display or visualization.

The benefit of 3D data visualization in process control depends on operator's task. According to Rasmussen's ladder model [8] the procedure of information processing can be subdivided in three steps: knowledge-based analysis, interpretation and knowledge-based planning of the activity. The application of 3D process data visualization could be beneficial in the first step to detect the appropriate action, to observe data, and to recognize system's condition.

However, most research works on usability are limited to virtual reality or the data visualization with static quasi-3D visualizations.

B. New approaches in interaction with 3D elements

The aspect of 3D visualization of process data in combination with interaction is rarely explored. According to Witmer and Singer [9] interaction with a 3D scene causes an increase of presence. Presence is defined as the sense of being present in a virtual environment, i.e. effects that influence the cognition of a state, the bonding to an event or the immersion into the virtual environment also influence the feeling of presence. Witmer and Singer specify four main factors from which two can be recognized as relevant for the task of monitoring process data:

Control factors: degree of control, immediacy of control, anticipation of events, mode of control, modifiability of physical environment.

Sensory factors: sensory modality, environmental richness, multimodal visualization, consistency of multimodal information, degree of movement perception, active search.

An increase of control can be achieved by interaction with the 3D scene. Schönhage's [10] approach is based on the DIVA Java 3D-collection that implements five different kinds of interactions, so called behaviors. Amongst others, Schönhage provided interaction that enables to display additional information by mouse clicks / keystrokes or actions that move or rotate the 3D elements. In our HMI design these behaviors can be used to change viewpoints and to recognize information better.

Interaction differs not only in its functionality and the way it influences the provided information. It also brings along different kind of difficulties in its handling. Consequently, learning effort for different types of interactions vary.

To evaluate the benefit of interaction in process data visualization, appropriate interactions that increase the available information but not too difficult for novice users to handle, need to be discovered. Therefore, as first step the behavior "rotation" was evaluated as it is known from other applications like computer games and users might be slightly familiar with it. Other interactions need to be analyzed later on.

III. Learning of Process Knowledge

A. State of the Art

In plant manufacturing industry, besides gas & oil or chemical plants, operator training is often realized as training on the job. The commissioning staff of the manufacturer and/or experienced operator teach novice operators based on their own mental model of the process.

If a model-based description of the process is available or can be developed, operator training systems (OTS) can be applied. An overview of available OTS and classification based on its functionality is given by Kroll [11].

Research in the domain of OTS in plant industry centers mainly on the technical realization and the system architecture of the systems [12]–[15], the didactical aspects and their implementation [14]; [16] as well as the intelligent assistance of the operator during training [14].

The dynamic process behavior needs to be modeled in the OTS. OTS often uses the original HMI screens to display the state of the process, the values of the process variables and the input options for operators. A subsidiary simulation of the process calculates the new state of the system based on the actual state and the operators' intervention. One main advantage is, that these simulation based OTS can be used before or during commissioning without the need for real process data.

B. OTS based on historical process data

Model-based OTS are one possibility to train dynamic process behavior to operators. However, it is not always possible to identify the process model. In this case, another currently rarely used approach is to train the operator based on real scenarios with real historical process data from similar plants. Engineers are more prone to using knowledge from other similar and familiar situations to solve a new problem than making time-consuming analysis [17]. So-called scenario-based OTS [18] use this effect and teach the operator representative sequences from the process in order to built up a mental model. One major disadvantage for this type of training is the need for data from the real or a comparable process (plant). Furthermore it is only possible to train recorded scenarios with the enclosed operator interventions and the process can not be simulated.

Most of the systems use static 2D trend charts (freeze images) for data visualization. In this case a predefined time range is displayed and can be analyzed by the operator. To analyze the dynamic behavior of the process the time range has to be either enlarged or manually shifted. Some OTS provide a functionality that is comparable to the slider [12]. However, these systems only use 2D displays and the combination of 3D visualization with slider functionality is not implemented in industrial applied OTS yet.

As a matter of fact, the benefits of different types of training (with or without slider) are not scientifically analyzed yet and this will be evaluated in an experiment that is described below.

IV. Hypothesis of the Benefit of Interactions in Process Data Visualization

The main task of an operator in a plant is to monitor the process to detect error conditions as fast as possible in order to keep the production of rejected material (waste material) as low as possible and to avoid human or machinery damage. In [19] the hit rate of error recognition was already analyzed. The combination of the right identification and the right reaction of an error was defined as a hit. It was shown that 3D process data visualization that includes interaction with the 3D scene, leads to significant better error detection (level of significance: 5%), if the problem is complex. However, interaction with the 3D scene implicates additional activities for the operator that may require additional processing time for the operator. It should be verified how interactive 3D process data visualization effects the reaction time during error detection. Reaction time is defined here as time between the start of a problem and the recognition of the problem by the subject.

The following hypothesis was deduced:

3D process data visualization with interaction leads to higher reaction time during the detection of errors.

The increased reaction time would reduce the approved benefit regarding the hit rate. Therefore it is necessary to combine the analysis of both, reaction time and hit rate to evaluate the benefit of 3D process data visualization in process control.

V. Experiment

In the following the experimental set-up will be derived based on the application example, an industrial production process.

A. Application Example

For the empirical evaluation of the hypotheses an appropriate application process has to be used. The process has to meet special requirements for the reasonable use of 3D visualization. Wickens [7] claims the necessity for integration of information to valuate the actual state of the process.

Based on the authors' experience [3], a continuous thermo-hydraulic press in timbre industry application was chosen for the experiment. The hydraulic press is used to produce different kinds of fiber boards, e.g. particle boards or medium density fiber boards (MDF). A glued material mat is pre-pressed and optionally preheated before it runs into the continuous press where it is pressed between two moving steel belts. The heat, that is necessary for the technological process, is transferred by calibrated roller rods from the heating plate to the steel belt. Hydraulic cylinders generate the pressure to press the material mat to the set values of distance and density. The cylinders are located equally spaced along the whole length and width of the press. The thickness of the mat is measured by means of distance transducers at the outer edges of the steel belts and is controlled by increasing or reducing the pressure. Important data, like temperature of the heating plate, thickness and pressure are continuously measured and displayed for the operator in the control room. Based on the actual process date and his knowledge about the process the operator decides how to take corrective actions on the process.

In the described application example multiple dependencies exist between different process factors, e.g. pressure and distance (fig. 1). The material has to be pressed to the set distance without exceeding the maximum pressure. For decision-making, both process values have to be observed and correlated across and along the press.

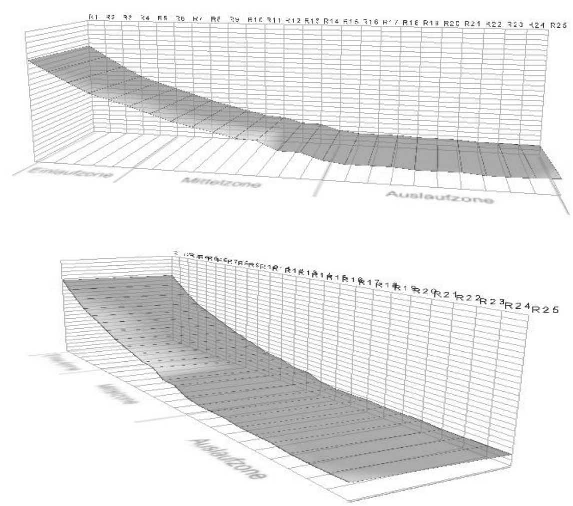

Figure 1. 3D visualization of distance with different viewpoints

B. Design and conduction of the experiment

The subjects' task in the experiment was to observe and to control the described application example. The experiment was divided into three phases: audio-visual training, exploration phase and operation phase.

In the audio-visual phase, the subjects watched a video that explained the application process. The relevant process factors and their interrelations were specified. The critical process situations and their symptoms were described. Furthermore, the video introduced the process visualization and the options for corrective actions.

Subsequently, the subjects move into the exploration phase. Firstly, the subjects reconstruct the information from the video and comprehend the process behavior and the scenario based on simulated process data. Secondly, the subjects verify the obtained knowledge in a testing phase where they had to operate the process and got feedback about the correctness of their interventions.

In the operation phase, the subjects had to control the process. They had to decide whether they were confronted with normal or with critical process conditions. In case of a critical situation, they had to take an appropriate corrective action. During the observation and control of the process they had to execute two additional tasks, i.e. hand writing product data on a protocol data sheet and communicating with colleagues in a chat instead of a walkie-talkie in a real plant (referring to Wicken's theory a second task was introduced, which indicates also the work load). The subjects had to pass the same selection of situations twice in random order. All actions of the subjects, e.g. error response time, were automatically recorded by the system. Additionally, the heart rate was measured during the experiment to evaluated physiological factors like stress.

To date, the experiment was executed with 70 subjects (students of different fields of study). All subjects had no previous knowledge about the process. To allow the comparison between 2D and 3D visualizations as well as the comparison of the different variations of training the subjects were divided randomly into five groups, each group with 14 subjects. The variations of training (freeze image, slider and slider with interaction) were combined with 2D and 3D visualizations (table I). The training with slider and interaction was evaluated only in 3D because 2D does not allow comparable interaction features. The training conditions were derived to examine three different modes of presence. The classical training (freeze image in 2D or 3D) mode, which is also the lowest mode, has figures showing critical situations and giving verbal instructions. The slider mode (2D or 3D) displays the development of a critical situation. Therefore, should provide more information to detect the critical situation. Training with slider and interaction (only 3D) should generate the highest presence because the interaction give subjects the opportunity to feel more involved in the process.

Additionally, different questionnaires were included to examine attentiveness, self-assessment and feedback on presence etc. After the operation phase an interview was conducted to analyze the individual mental models

TABLE I. EXPERIMENTAL DESIGN
(TRAINING OPTIONS AND DIMENSION)

Dimension of HMI	Training with freeze image	Training with slider	Training with slider and interaction
2D	group 1	group 2	---
3D	group 3	group 4	group 5

C. *Experimental environment*

For the evaluation an experimental environment, which should be as realistic as possible compared with the real application, was developed. The main challenge was to find a balance between the approximation to the real operator task in a control room and an experimental environment that does not overstrain novice subjects.

The environment is based on a PC with two monitors displaying 4 different diagrams. Depending on the provided scenario, the subject had to combine the information displayed in these diagrams to identify the problem and to deduce an appropriate input reaction. On an adjoining tablet PC they had to execute additional tasks like hand writing production protocol. Both PCs were connected and all relevant actions of the subjects on both systems were recorded in one database according to their timeline (more details to the environment are given in [20]).

VI. RESULTS OF THE EXPERIMENT

The following results refer to the experimental evaluation with 70 subjects. Table II gives an overview of the number of subjects in the five groups. Due to technical problems the results of one subject in group 5 could only be recorded in the first trial. However, these results were included in the analysis.

TABLE II. ASSIGNMENT OF SUBJECT TO TRAINING VARIATIONS
(GROUP NUMBER TABLE I)

Group	1	2	3	4	5
subjects	14	14	14	14	13,5

3D process data visualization with interaction leads to higher reaction time during the detection of errors.

For the evaluation of the hypothesis, the mean value of the reaction time was calculated for each subject. As not all of the subjects successfully handled the same number of problem situations, it is necessary to consider a weighted average value for each group.

To evaluate the performance of the subjects in the two operating phases in the different groups, the reaction times were regarded in combination with the hit rate.

Fig. 2 shows the performance of the subjects over all problem situations – complex and simple – in the different groups. Group 5 not only obtained the highest hit rate; they also achieved faster reaction times. However, the results showed no significant differences, neither in hit rate nor in reaction times.

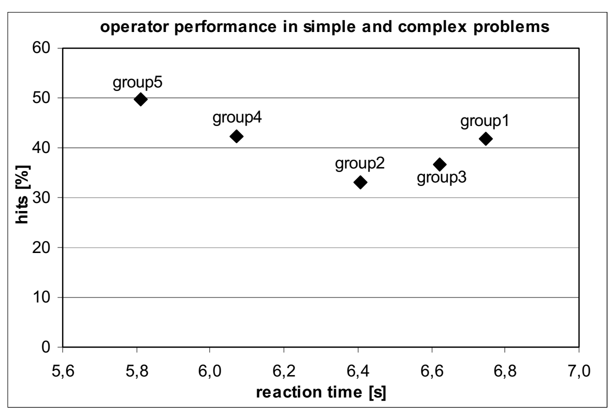

Figure 2. operator performance in simple and complex problems divided according to training condition

For further analysis, the problem situations were analyzed separately regarding complex and simple problems. Fig. 3 shows the results for simple problems. Group 4 shows faster reaction times than the other groups, but the hit rate is lower than group 5 and group 3. However, the hit rate and reaction time were also not significant.

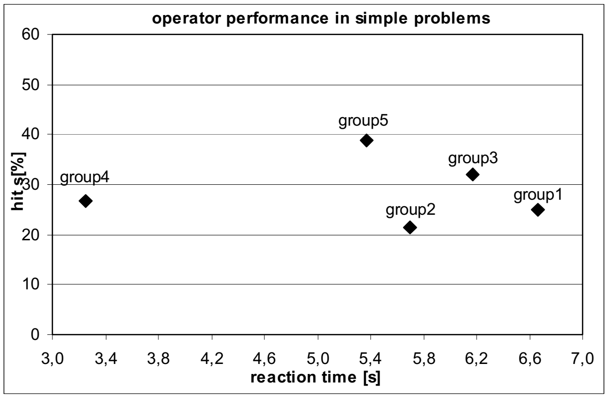

Figure 3. operator performance in simple problems divided according to training condition

Finally, the results for the complex problems were analyzed. Group 5 not only achieved the highest hit rate but also the lowest reaction time (fig. 4). Regarding the hit rate, a significant advantage was published in [19]. However, the advantage in reaction time is not significant.

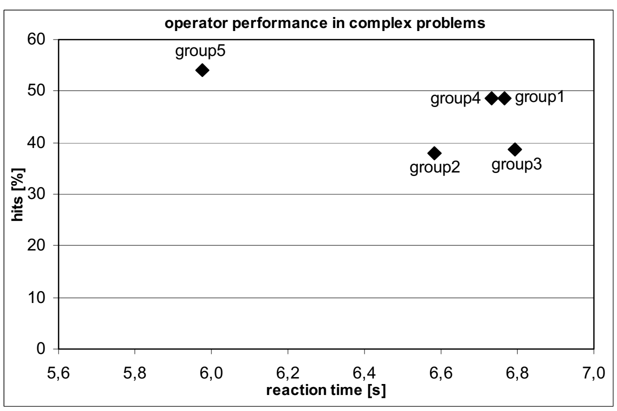

Figure 4. operator performance in complex problems divided according to training condition

VII. Discussion of the Results

With regard to the hypothesis, the results show that interaction with the 3D scene does not lead to significant higher reaction times. In contrast, group 5 – 3D with interaction – actually needs less time for the detection of errors in complex problem situations than the other groups. Although the results of the reaction times are not significant, a combined inspection of the results, i.e. the hit rate in combination with the reaction time, shows an advantage for the interaction group. As it was verified that all subjects used the interaction with the visualization, this effect could be a hint the fact that complex problems can be recognized faster with the aid of an interactive adjustment of suitable viewpoints. The gain time that is the time saved through the improved view point, seems to be higher than the time that is needed to achieve this view point. However, the number of interactions with the scene and the time that was spend for adjusting the viewpoint were recorded during the experiment but have not been evaluated yet.

Regarding the simple problem, similar results were obtained. It was also verified that all subjects of group 5 used the interaction. It appeared that the average reaction time in group 5 is higher than in group 4, but lower than in the other groups. However, the hit rate in group 5 was higher than in group 4.

VIII. Summary and Outlook

In this paper an experiment that evaluates the influence of different types of visualization (2D, 3D/ interaction) and training on reaction time in process control was described. It was shown, that 3D process data visualization with interaction has no effect to higher reaction time. In complex problem situations, subjects that used interaction not only achieved the highest hit rate but also the lowest reaction time as compared to the other groups.

The influence of the interaction activities will be focused. In doing so, it will be evaluated if a correlation exists between the number of interactions and the reaction time in a specific problem situation or the overall hit rate.

Based on the results of the described experiments, further possibilities of interaction with the visualization will be analyzed regarding the benefit for the operators' tasks. In a following experiment, it will not only be possible to rotate but also to zoom into the screen to enlarge visualization's areas.

Up to now, only the influence of 3D for the task of data analysis and error detection has been experimentally evaluated. However, it is also possible to use 3D for process interventions. For this reason, a post-test will be conducted, where one part the subjects will have to enter the corrective values via a 3D interface. For example, it will be possible to directly change the distance set point by manipulating the corresponding area on the surface of a 3D visualization. It will be evaluated, whether this kind of interaction has a positive influence on the processing time that is defined as the time from the identification of the error to end of the corrective intervention.

Furthermore, the influence of the operator's experience regarding the process knowledge needs to be examined. As described, the experiments were conducted with students that were novices with regard to the technical process. It is expected that more experienced subjects will have lower average reaction time in the experiments. However, it needs to be evaluated if the influences of training and data revisualization differ depending on the subjects' experience.

Acknowledgments

The project is funded by DFG (German Research Foundation) under VO 937/7-1 from 5/2007 to 4/2009.

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