Supporting Operators in Process Control Tasks—Benefits of Interactive 3-D Visualization

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***Abstract*—In today's automated systems, the plant operator is confronted with a growing amount of diverse and distributed data about the plant process. For process control, the operator has to observe, interpret, and integrate the process data to form a basis of decision making for input parameter settings. This difficult task is prone to errors and can quickly result in insufficient product quality. An effective display design can support the operator and mitigate this effect. Two experiments investigated whether the integration of process data in 3-D visualizations could increase the operators' performance in this environment. The first experiment examined benefits of improving reaction times and error rates for problem detection and corrective inputs. The possible reduction of the operators' workload was examined simultaneously. Additionally, experiment 1 offered insights on how interaction with the 3-D visualization could further improve the appropriateness of selected process settings by the operator. Results of this experiment showed 3-D and interaction as beneficial factors for the detection of problems in process control tasks and participants showed a low mental workload compared to 2-D presentations. In the second experiment, the scenario was extended by the investigation of a 3-D input design. In comparison to regular 2-D input, results showed that a combination of 3-D input and interaction exhibited higher accuracy in problem solving.**

***Index Terms*—Human–computer interface, human performance, process control systems, 3-D, visualization, workload.**

I. Introduction

CHEMICAL plants, steel mills, as well as particle board or film producing plants are automated, but still need skilled operators to interact with the process and the machine settings to optimize the automatic process control and/or to handle abnormal situations [1]. Data as well as video surveillance from the process and machine settings are visualized on several monitors in a centralized control room. In addition to the actual process values and set values, the operator has to monitor the devices' status as well as alarm lists. Additionally, operators in control rooms have further tasks such as keeping shift records or communicating with colleagues about the process states. This leads to an increased workload and potentially to an overload for the operator [2]. Furthermore, the operator often has very limited time to make control decisions in reaction to poor product quality or machine failures.

Analysis of the systems' status in process control requires the combination of a variety of data/process values from different sources. Building relations between these different data and integration of data to get beneficial information are complex tasks for operators [3]. Variables are interrelated and interact with each other [3]–[5]. Therefore, data should be well organized, and the difficulties to identify important data should be reduced, e.g., by visualizing aggregated data as a single piece of information. For a better evaluation of beneficial visualization approaches, a deeper understanding of human models in human–machine interaction is necessary.

Following Kang *et al.* [6], and Card *et al.* [7], the information channel contains knowledge about monitoring. The short-term memory influences the capacity of the channel. A cognitive and a decision processor lead to decisions and are responsible for motoric reactions. However, task difficulty and complexity depend on the information flow to the human processor, i.e., environmental factors (e.g., control monitors) affect the task performance.

One possibility is to develop an adequate visualization, which supports the operator in understanding the actual working processes. Up to now, different 2-D diagrams, graphs, and tables are the state of industrial practice in process control to visualize process data. However, to get beneficial information from the growing amount of integrated process data that have to be observed by the operator, these 2-D human–machine interfaces might not be able to meet the requirements regarding the complexity in process control [8].

In the field of information visualization, 3-D visualization is state of the art. Many tools that deal with analysis of large datasets currently use 3-D representations to help extracting information from large amounts of data and to identify relationships and patterns. In process data visualization, 3-D representations could support the operator in a similar way in interpreting and integrating large amounts of data and in making decisions on appropriate parameter inputs. However, in the environment of process control where representation of measured data and process variables is required for a fast and reliable fault detection, 3-D visualizations have rarely been studied.

The main contribution of this paper is to answer the questions: How can the operator be supported in his/her task to observe, integrate, and interpret process information and to select the appropriate input parameter settings for the process control system? This paper investigates whether 3-D visualization and interaction can reduce mental workload and complexity in this field.

A continuous thermohydraulic press was used as a basis for the two experiments in our study (see Section III). The first

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experiment (see Section IV) focused on operator efficiency, comparing an integrated 3-D - with a 2-D -visualization, measuring accuracy, time, and mental workload. As the first experiment revealed that interaction with 3-D is beneficial, a second experiment was conducted, focusing on 3-D plus interaction and proposing a more advanced interaction mechanism (see Section V). The results revealed that the benefits of 3-D visualization combined with interaction were accompanied by a higher mental workload, whereas 3-D without interaction is not. In the results of both experiments, 3-D visualization plus interaction showed improvements in accuracy, but insignificant differences in reaction times (see Section VI). Overall, 3-D visualization showed to be a possibility to improve process control, especially for complex tasks. In the final section, a conclusion of this research and an outlook on future work are presented (see Section VII).

II. Related Work

Various works deal with the topic of 3-D data visualization. Information retrieval from different data sources, mental workload of the operator, interaction with the 3-D scene, and navigation through data are important in this field of research.

A. Three-Dimensional Data Visualization in Process Control

To decrease operators' mental workload in monitoring and control tasks, information can be integrated into one visualization. Wickens' proximity compatibility principle (PCP) [9] states that tasks that require the integration of information benefit from a perceptual proximity of the visualization. The integration of information is particularly beneficial for the detection of complex problems. Relevant information for a common or mental task should be arranged close together or integrated when a task requires the simultaneous processing of information. This reduces the operators' cognitive workload for the integration of several data sources.

Wickens *et al.* [10] showed in an experiment that the integration of related data can be increased by adding a third dimension within the visualization.

However, John *et al.* [11] examined that the benefits of 3-D visualization depend on the type of task. On the one hand, 3-D is beneficial for shape understanding when the integration of data from different sources is required for specific tasks and consequently reduces the cognitive demand. On the other hand, it decreases the performance in tasks that require the identification of relative positions. Identification of precise values could hardly be achieved using 3-D displays.

Beuthel [12] and Hoppe *et al.* [13] showed the advantage of 3-D in process visualization compared to 2-D in an application within coal-fired power plants and electric power grids. Both studies measured and compared the reaction time and the processing time to handle problems presented in 2-D and 3-D visualization. Husøy and Skourup [14] developed a 3-D model of a plant for control systems. It allows operators to access various data and data from different sources integrated in a 3-D model, e.g., by selecting specific areas to retrieve additional information about components.

Spatial visualization in terms of 3-D process visualization may remedy the deficiencies by supplying the operator with process information in a way that is adapted to the human perception and information reception. Smallman *et al.* [15] describe several benefits of 3-D compared to 2-D displays, under the condition that the third dimension is not only decorative but provides essential information [16], [17]. First, they state that 3-D displays seem to be ecologically more plausible, because the retinal pictures are perspective projections of the environment. However, this argument does not take into account that various monocular and binocular spatial cues are responsible for creating a 3-D projection of the environment. Second, 3-D displays reduce users' mental workload through the integration of all three spatial dimensions into only one representation (see also [9]). Third, users seem to prefer the familiarity and simplicity of 3-D displays [18]. However, the authors also point out the risk of ambiguity of 3-D displays that can result in problems with exact position determination.

Furthermore, Woods' "visual momentum" considers each glance on a data field as independent of the previous glance and consequently as a new display. High visual momentum supports the rapid comprehension of data in transition to a new display. Therefore, "the amount of visual momentum supported by a display system is inversely proportional to the mental effort required to place a new display into the context of the total data base and the user's information needs" [19]. The amount of visual momentum depends on the compatibility of display system characteristics and characteristics of perceptual processing and selective attention. A display is informative if it provides a visual frame as reference for describing the relationship of data points. According to the visual momentum, spatial representation of data supports human information processing and improves user comprehension. Visual momentum also reduces mental workload by information location and integration as well as organizational changes in mental processes [19].

The approach of ecological interface design aims at building a framework for systematical examination of data to identify dependences of process parameters that support the interaction with the system [19]. Visual data presentation takes the requirements of the work domain and task analysis into account. Therefore, complex relationships and constraints can be visualized so that the user is supported in problem solving, decision making, managing, and anticipating the process, especially in unfamiliar situations [20].

In addition to compatibility and perceptual proximity in data visualization, the compatibility of stimuli and responses have to be considered [4], [19]. Location compatibility describes the spatial arrangement of stimuli and controls, i.e., controls should be located next to the relevant displays. In case this perceptual proximity cannot be realized, congruence—the mapping between the spatial array of controls and display indicators—is important. The onset of a stimulus activates a tendency to respond in the associated location [4]. Movement compatibility describes operators' expectations of how the display responds to the control activity. The changes in the display should be consistent with the movement direction of controls.

B. Operators' Mental Workload in Process Control

Supervisory control of semiautomated processes requires the operators' monitoring and correction activities in critical situations. Therefore, the development of systems for control rooms must consider the need to keep the operator in the loop. The integration of data from various sources requires high performance in terms of the operators' attention and leads to a mental overload in critical situations. Additionally, the observation of a normal process for a longer period of time bears the risk of the operators' fatigue and inattention and, hence, out-of-the-loop situations with a high risk of poor decisions in process control [20]. An intermediate level of automation can support the integration of human and control system, reducing the susceptibility of vigilance, loss of system control or situation awareness, and, consequently, enhance system safety [21].

Furthermore, for traffic information in cockpit displays, Thomas and Wickens [22] tested the usage of 2-D versus 3-D displays. In three experiments, they investigated the influence of display dimensionality on performance. No effect on the resolution success in conflicting flight situation could be found. The induced time pressure increased the workload and negatively influenced performance with both dimensionalities equally. Similarly, interaction during process control (see Section II-C) could be an approach to reducing mental workload, i.e., reduction of fatigue.

The appeal of 3-D often results from the capability to develop complex shapes, which integrate a variety of related data into one visualization [23]. In process control, the complexity of production processes leads to a great amount of simultaneously presented information on several screens to observe the process, and thus to difficulties to recognize deviations from normal process early.

C. Three-Dimensional Object Interaction and Navigation

For the representation of 3-D scenes on standard 2-D displays as currently used in industrial control rooms, additional mechanisms for depth perception are required. The 3-D effect is achieved by masking, texturizing, perspective views, shadows, relative sizes of objects, and sharpness [24]. In computer-based systems, motion parallax can also be used. These mechanisms suggest a depth effect to the user, while still providing only a 2-D image. The human mentally converts it to a 3-D scene.

Interaction with the 3-D scene is also a medium to support the 3-D perception. In virtual reality (VR), interaction is used to move through a 3-D scene suggesting presence to the user in the scene. Interaction is an important factor to control the virtual environment and provides a sense of involvement in the 3-D scene. This increases the feeling of presence [25]. A method for realizing interaction with a 3-D visualization is freely selectable viewpoint using 3-D rotation. Mouse use for free rotation of objects around a selectable axis in 3-D space is perceived as a time-efficient and precise possibility to gain more information about the moved object [26].

In the last couple of years, 3-D and interaction techniques were predominantly investigated for gesture controlling [27] and 3-D input devices for games. These fields can be relevant in an industrial context, although research of gesture based interaction indicates that natural gestures are more beneficial for situations with a reduced cognitive workload compared to sketched surrogate gestures [28]. Investigations considered interaction concepts in VR, but not for integrated 3-D data visualization and interaction in terms of rotation.

Another crucial effect that can be traced back to large amounts of data being displayed is the keyhole effect. It describes the tradeoff of digging deep into information about one area of the system while disregarding other system components [14]. A decrease of the keyhole effect could be achieved by providing a better sense of context, a quick access to an overview, and more effective navigation methods in the control interface. For attentional tunneling, i.e., the allocation of attention to a particular source of information, Regis *et al.* [29] developed a system to detect these effects. In time-critical systems, Crandall *et al.* [30] examined a recommendation system to support operators' attention allocation, yet dictating attention allocation did not increase effectiveness, and operators became frustrated by forced services of the system. Nevertheless, users preferred the guidance by the recommendation system, if a choice to follow the recommendations was given.

In VR, interaction techniques have been classified and evaluated for selection and manipulation of objects, as well as navigation through a 3-D scene by Bowman *et al.* [31], [32] and Poupyrev and Ichikawa [33]. They developed design guidelines and thus facilitate the selection of appropriate modes of interaction with the 3-D environment. In addition, different types of interaction devices were investigated (e.g., trackball, mouse, VR goggles, and gloves). However, most control rooms are currently not designed for VR; thus, the evaluation and design guidelines, which specifically relate to VR, can only be partially adapted to the field of process control.

Chen's "virtual trackball" experiments have shown that a free rotation around a freely selectable axis is perceived as natural and intuitive. This kind of interaction was most efficient with lower reaction times compared to other more restricted rotations around several axes [26]. If fine and accurate adjustments of objects are required, free 3-D rotation is less beneficial.

In addition, mouse-based interaction for a 3-D rotation was examined, and general principles for rotation techniques were formulated [34]:

1) Similar actions should provoke similar reactions (movement compatibility [4]).
2) The direction of the rotation should match the direction of the 2-D input device movement.
3) The 3-D rotation should also be transitive.
4) The control-to-display (mapping of device movement and system response) ratio should be customizable.

Bade *et al.* [34] examined several 3-D rotation techniques and concluded, in contrast to [26], that the best interactive 3-D rotation is a two-axis movement (horizontal and vertical mouse movement), and they further hypothesized that the best interactive 3-D rotation results from an appropriate combination of flexibility and user-guidance. The direction of rotation always equals the direction of the mouse movement.

Husøy and Enkerud [35] developed a process control interface with improved interaction methods. For example, the movements in the interface should provide information of the relations between several parts of the interface so that an overview level was not necessary. Additionally, through zooming in and out, current issues should clearly be located in their immediate surroundings. Thus, in preliminary user tests, interactions such as zooming showed a beneficial effect to reduce the negative impacts of the keyhole effect.

A comparison of 2-D and 3-D and, additionally, the effect of interaction as defined by adjusting an alternate viewpoint were examined for cockpit settings [22]. The rotation allows resolving the spatial ambiguity in 3-D displays to provide a more intuitive picture of spatial environment. However, there is a risk of choosing an unsuitable perspective, increasing ambiguity. Experiments revealed that pilots consistently used interactivity of viewpoint changes, but the interactivity decreased with induced time pressure [22]. The viewpoint manipulations reduced the 3-D spatial ambiguity in most cases and, therefore, lead to a comparable performance to that with 2-D displays. Results suggest that a minimal amount of interaction is sufficient to eliminate the ambiguity influenced performance deficiencies. The authors proposed that training for effective selection of optimal viewpoints with a minimal amount of time and effort would increase the positive effect of interaction in 3-D displays.

The previously mentioned studies have shown that 3-D visualizations for complex problems can be beneficial. Studies in the domain of process control, taking into account common external influences such as additional concurrent tasks during process operation, are lacking. However, an operator in a real control room is entrusted to handle several concurrent repeating tasks, distracting from the main task, the monitoring, and control of the process.

In addition, the influence of interaction has not been sufficiently studied in the context of process control. On the one hand, 2-D screens available in today's control rooms only allow for the effect of 3-D through interaction with the scene. Therefore, interaction supports the 3-D visualization concepts. On the other hand, however, interaction can also be interpreted as an additional task, which distracts the operator. The time required for the interaction can have a negative impact on the problem detection and reaction time.

III. Experiment Introduction—Application Example Thermohydraulic Press

To study the effects of 3-D visualization, interaction, and control in process control, two experiments were conducted with a task setting comparable to a realistic control room situation.

The experiments utilized a continuous thermohydraulic press in the particle board industry that required human interactions with the process control system during abnormal events. The authors have extensive experience in equipping this process as well as access to the machine supplier and its customers operating similar plants [1]. The application example of the pressing process provides complex and elementary problems, i.e., problems with a high degree of integration and low degree of integration of information, respectively. According to Wickens and Andre [9], the complexity depends on the degree of integration of information. Therefore, the complexity of the task, which is determined by the interconnectivity and the dynamics of the system variables [3], is crucial in demonstrating an advantage of 3-D visualizations over 2-D.

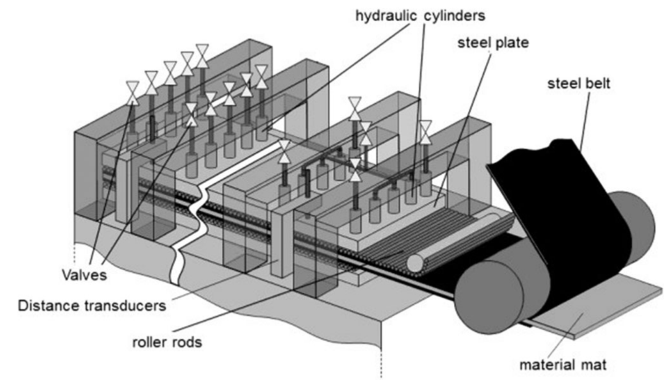

Fig. 1. Thermohydraulic press in particle board industry.

The thermohydraulic press is used to produce different kinds of fiber boards [1] (see Fig. 1). The glued raw material (wood chips) runs into the hydraulic press and is pressed between two moving steel belts. The pressure, needed to compress the material mat, is generate by hydraulic cylinders and transferred by roller rods from a steel plate to the material mat. The hydraulic cylinders are located equally spaced along the whole length and width of the press. Distance transducers measure the thickness of the material. The thickness is controlled by increasing and reducing the pressure in the hydraulic cylinders. All relevant data, such as thickness, temperature, and pressure, are displayed in the control room on various displays.

In a semiautomated process, small deviations of the normal pressing process are adjusted automatically, but in some cases, the operators' corrective input is required to adjust the steel belts' distance, which indirectly changes the pressure transferred on the material.

During the process, elementary and complex problems can occur. An example of an elementary problem is the scattering of too much material, which leads to insufficient product quality (not the required thickness of the fiber board). To identify this problem, the operator has to observe only one process value in a single diagram (distance of the steel belts). Torsion of the steel belt is a complex problem and can be caused by partially incorrectly adjusted set values. During the further process, the automatic control tries to achieve the required thickness of the fiber board. This leads to a torsion of the steel belt and in the worst case to the destruction of the steel plates and thus to a loss of production. For the detection of this complex problem, the process values relating to distance and pressure have to be monitored at different locations simultaneously.

The complexity in this application example and the resulting degree of integration are caused by the amount of information needed to be brought into relation. Additionally, the quantity of information sources (diagrams such as in Fig. 2), as well as the identification of the correct sources for the needed information

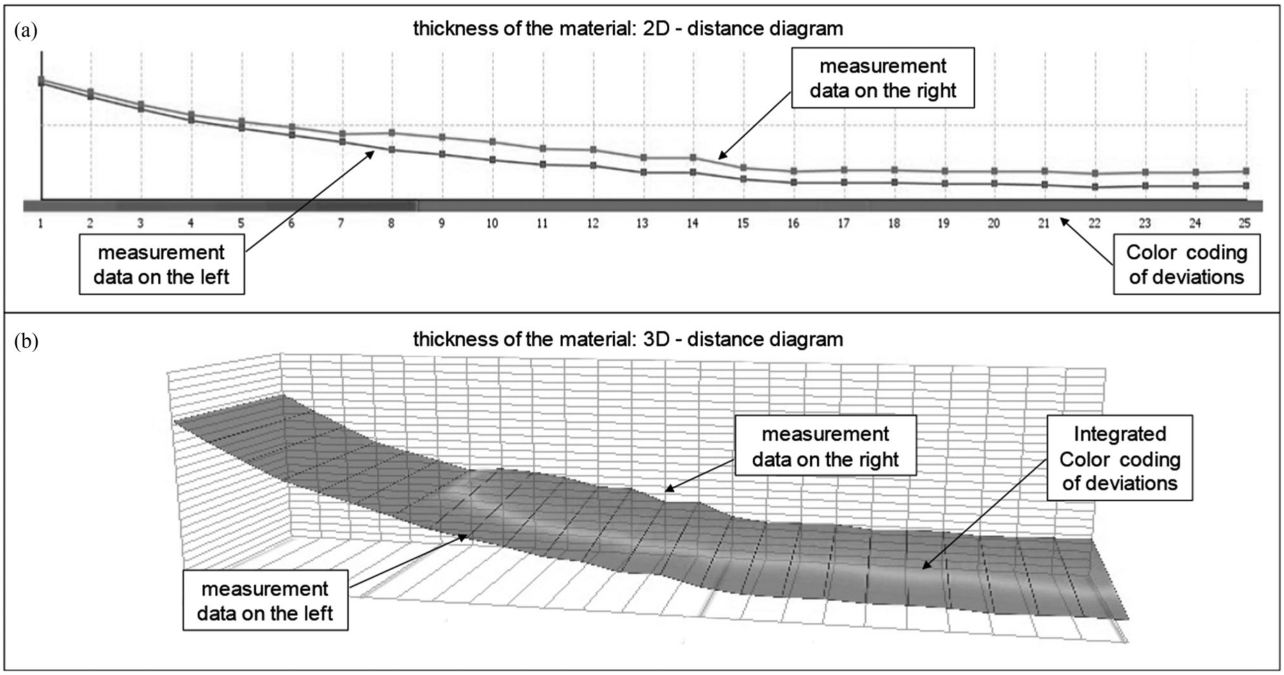

Fig. 2. Thickness of the material in the thermohydraulic press: (a) 2-D and (b) 3-D visualization.

further increases the complexity. In the application example, the correlation of information and location within the process is additionally important for identification of the process state.

IV. Integrated Three-Dimensional Visualization and Interaction—Experiment 1

The first experiment examined the efficiency of a 3-D visualization of process data and compared it to 2-D visualizations for a thermohydraulic pressing process. Furthermore, it was tested whether 3-D integrated visualizations facilitated the operators' work task and thereby reduced their mental demand. Additionally, this experiment investigated if interaction is beneficial in process control.

In the simulation, two screens were used to monitor the production process. Three sections of the process were visualized in four graphs. The first diagram showed the first section preceding the hydraulic press, the forming line, where the material is scattered onto the steel belt. The next section, the hydraulic press, was visualized in two diagrams: one for pressure that is transferred onto the material and another one for the thickness of the material (Fig. 2(a): 2-D and 2(b): 3-D). Finally, the fourth diagram illustrated the subsequent measurement of the final product at the end of the process. With these four diagrams, most problems in the hydraulic press (elementary and complex) can be detected.

Diagrams in 2-D and 3-D visualized the same information of the process. Both solely differed in the manner of the visualization. For instance, while distance in 2-D was visualized using several lines for data of the process on the sides of the press, the 3-D visualization contained an interpolated surface plot [see Fig. 2(b)]. Additionally, both 2-D and 3-D used color coding. Green indicated normal process values, while deviations were emphasized ranging from yellow to red, depending on the degree of difference to normal values. Interaction in this experiment describes the possibility to use the 3-D rotation around all axes to freely choose a viewpoint (camera position) for each 3-D graph by mouse movement after clicking on the diagram.

A. Hypotheses

For the current study, it was hypothesized that the 3-D visualization of the production process leads to better performance in the process monitoring task. Furthermore, the mental workload was thought to decrease in 3-D visualization conditions, because information integration is facilitated, and 3-D plus interaction has comparable mental demand as 3-D without interaction. Additionally, interaction (change of viewpoint) was expected to have a beneficial effect on problem detection, i.e., a lower error rate than 3-D and 2-D, and is not time consuming, i.e., does not significantly increase reaction times. Additionally, interaction is not perceived as an additional task. Therefore, the following three hypotheses arose.

(H1.1) Three-dimensional visualization of process data leads to lower error rates and reduced reaction times in process monitoring tasks.
(H1.2) Three-dimensional visualization decreases the mental workload.
(H1.3) Interaction has a beneficial effect on problem detection (lower error rates).

B. Method

1) Participants: The participants were 70 students (34 males, 36 females) from four universities rewarded with credit points or monetary gratifications for participation. The

TABLE I
EXPERIMENTAL GROUPS

	Training		
	Freeze image	Slider	Slider plus interaction
2-D	Group 1	Group 2	—
3-D	Group 3	Group 4	Group 5

age ranged from 18 to 41 (M = 23.19, SD = 4.055). The students studied science (32) and engineering (21), but also the humanities (7), computer science (7), and others. Thirty-nine participants indicated prior experience with 3-D visualizations, predominantly through games.

2) Experimental Design: The study employed five groups (between subjects' design; see Table I). Students were assigned completely randomized to different kinds of training (freeze image versus slider) and different data visualizations (2-D versus 3-D). The slider is a process data player that allows the subject to move through recorded data across a certain time frame by a scroll bar to learn the process and thus support the operator in training to explore different problem situations [36]. The fifth group had the additional possibility to interact with 3-D visualization (3-D rotation around all axes to freely choose a viewpoint) in training (in combination with the slider) and in the test section.

In accordance with the real process control task, two kinds of problems were used: two elementary and three complex problems. While the elementary problems were characterized by a single cause and the fact that only one diagram should be taken into account, the complex problems required the observation and aggregation of various parameters in one diagram or different diagrams at the same time to get the required information. Operators had to consider the interconnectivity of system variables and, consequently, needed to build relations between various data to react in an appropriate way.

3) Procedure: The experiment was divided in three sections.

a) Training section: At first, an audio–visual presentation about the functionality of the press was presented followed by a description of problem characteristics and required control inputs in case critical situations appeared (ca. 35 min). Afterwards, the participants were free to explore several problems according to their experimental group (see Table I). They were able to look at different states of each problem in detail and at a self-determined pace to gain an understanding of how problems arise and develop into critical situations. During the training section, FAQs concerning different aspects of problems and the press process were provided (10 min). An audio–visual presentation summarizing the problem characteristics followed (5 min). The training section ended with a training phase of process monitoring similar to the test phase, but additional feedback about correctness of input reaction was provided (20 min).

b) Test section: The test phase, divided into two sections, consisted of a monitoring task with 15 scenarios per section (seven critical and eight non-critical problem situations), which were shown in a sequence with simulated data. Each scenario contained one problem situation. During each data sequence, participants of the different groups (compare Table I) were instructed to press a button as quickly as possible whenever they detected a problem. Only one group (3-D plus interaction) had the possibility to interact with the 3-D scene (rotation of the diagrams). The sequence stopped and the subjects were asked to make previously learned corrective inputs (change of distance parameter). The effects of their corrective actions were not displayed. During the monitoring task, additional secondary tasks were included. Participants had to keep a protocol about the press process (check critical or noncritical situations) by recording them on the computer and chats with colleagues were simulated to achieve a situation similar to real work tasks.

c) Final experimental section: The final experimental section started with a semistructured interview about participants' mental models. Therefore, each participant was asked to label cards relating to the press process including states, processes, and elements and to sort them in a type of structure formation technique [37]. Finally, questionnaires of presence [25], mental workload [38], and self-efficacy [39] were provided. The whole experiment took about 150 min for each participant.

4) Measurements: The reaction time was measured from the starting time of a problem situation, i.e., the earliest time from which it was possible to react to a problem, up to the time at which they actually reacted by pressing a button. The input interval, reaching from the earliest to the latest possible time to react, was defined individually for each problem situations by experts.

In order to analyze user reaction errors, categories according to the signal detection theory (number of hits, errors, correct rejections, and false alarms) were computed in a first step and then aggregated to hits and errors per participant. In our experiments, errors were classified as follows:

1) false reaction to a critical situation;
2) correct reaction outside the predefined input interval (to early, to late);
3) no reaction on a critical situation.

Presence, mental workload, and self-efficacy of every participant in the five experimental groups were measured. Presence was measured by a questionnaire with scales for involvement, realness/control, and action alignment. The questionnaire of self-efficacy was adapted to the domain of process monitoring and control [39]. Mental workload was recorded with the NASA-TLX questionnaire [38] containing scales of mental demand, effort, time pressure, visual demand, and frustration. The sum of the scales indicates the overall mental workload. Performance was measured through the amount of errors (false or missing reaction) and hits (correct reaction in time).

C. Results

The analysis revealed an overall high error rate (58.2%). The lowest error rate was found for the group with 3-D visualization plus interaction (see Table II) resulting in the only condition with more hits than errors in problem detection (chi-square = 11.08, df = 4, $p = 0.05$). These results are confirmed by two nonparametric analyses which show no significant differences

TABLE II
ERRORS AND HITS FOR EXPERIMENTAL GROUPS

Group	Errors	%	Hits	%
2-D freeze image	97	57.74	71	42.26
2-D slider	110	65.48	58	34.52
3-D freeze image	110	65.48	58	34.52
3-D slider	92	59.74	62	40.26
3-D slider plus interaction	74	45.96	87	54.04

Fig. 3. Relation between accuracy and reaction time (speed–accuracy tradeoff).

between dimensions (Fisher test $p = 0.5$), but a trend when comparing the five groups (chi-square = 6.13, df = 4, $p = 0.10$).

Error rate should, however, not be considered separately from reaction time. Fig. 3 illustrates a speed–accuracy tradeoff which is also proved by a significant correlation between errors and reaction times ($r = -0.57$, $p = 0.01$).

Further analyses showed that 3-D interaction has the highest rate of accuracy and simultaneously a relatively low reaction time, which is proven by a trend for both variables (error: $U = -1.18$, $p = 0.119$, rt: $U = -1.55$, $p = 0.06$). Thus, *H1.1* (3-D visualization of process data leads to lower error rates and reduced reaction times in process monitoring tasks) is partially supported. Detailed considerations of reaction times are published in [40].

Additionally, the interaction analysis showed that all participants of the group used interaction, but the quantity of interactions scattered substantially from 5 to about 8000 recorded viewpoint adjustments per participant (M = 2852.36, SD = 2796.764). No significant differences between numbers of interactions used in problematic and nonproblematic situations or in elementary and complex problem situations were found. Finally, a relation of interaction and the kind of reaction (hits, errors) could not be identified.

Referring to *H1.2* (3-D visualization decreases the mental workload), the first step of the analysis considered the mental workload of the groups of participants [41]. The results indicate significant differences in the case of time pressure ($F = 4.631$, df = 4, $p = 0.002$). Furthermore, the Bonferroni test showed significant differences for the 2-D slider and 3-D freeze group ($p = 0.004$), as well as the 3-D slider ($p = 0.05$) and, by trend,

TABLE III
CORRELATIONS OF MENTAL WORKLOAD SCALES AND ERROR RATE

Mental workload scales	Error rate
time pressure	$r = 0.266$; $p = 0.05$
visual demand	$r = 0.261$; $p = 0.05$
overall mental workload	$r = 0.239$; $p = 0.05$

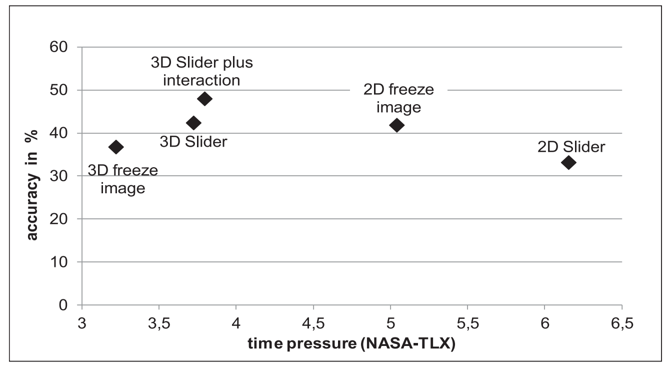

Fig. 4. Relation between accuracy and perceived time pressure.

the 3-D slider with interaction group. The participants in the 2-D slider condition perceived more time pressure than the other groups. Additionally, the error rate was significantly correlated with several mental workload scales (see Table III).

The relation of hits in different groups and time pressure is depicted in Fig. 4. The participants in the 2-D slider group perceived the highest time pressure in addition to the lowest hit rate. Furthermore, groups with 3-D visualization had a higher accuracy accompanied by lower scores in time pressure. Further analysis showed that in the 3-D slider with interaction group, the highest accuracy is accompanied with low perceived time pressure when comparing to the time pressure under the 2-D slider condition ($U = -2.574$, $p = 0.01$). Regarding H1.3 (Interaction has a beneficial effect on problem detection), the group using 3-D plus interaction showed low time pressure, joined by the highest accuracy.

Summarizing, the results of the first experiment indicate that interaction has a beneficial effect on error rate (H1.3). This includes relatively low perceived time pressure (H1.2). Hypothesis 1.1 was only partially supported.

Based on these results, it seemed advisable to analyze the interaction group in more detail to reveal the reasons for decreased time pressure but no significantly reduced error rates and reaction times. Therefore, different additional variables were analyzed: the correlation between the number of interactions and the number of hits, the time span between the beginning of a problem situation and the related interaction, and further aspects of interaction. All these analyses did not reveal any significant results or hints for the advantage of interaction. Neither relations to the kind of reaction nor relations the kind of problem could be accounted for.

Regarding the differences between the dimensionality, participants of the 3-D groups (except 3-D with freeze image) performed better in problem detection and experienced a lower

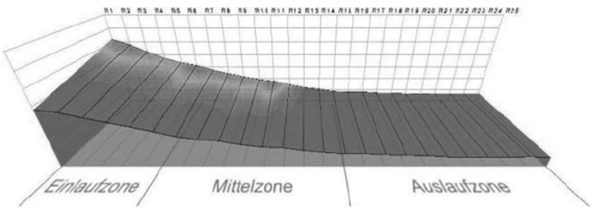

Fig. 5. Visualization of distance with additional height.

mental workload, but reacted a bit slower than participants of the 2-D groups. The interaction group achieved the best speed–accuracy tradeoff accompanied by a lower perceived mental workload (time pressure). The results are in line with the findings by Witmer and Singer [25]. The first experiment showed that free rotation of the diagrams around a selectable axis is at least partially beneficial for gaining information and consequently improving performance in process control. This kind of interaction is perceived as natural and intuitive, is efficient for the task [26], and does not increase the mental workload. The viewpoint manipulations support the accuracy in 3-D visualization. This supports the prior results of [22] that found that interaction resolves spatial ambiguity.

V. Advanced Interaction—Experiment 2

In order to replicate the positive results of the interaction group referring to *H1.2* and *H1.3* of the first experiment and to further analyze the reasons for increasing reaction times when errors are decreasing, 3-D visualization and interaction was further examined as a method for corrective input in a second experiment. Therefore, an additional 3-D input panel was developed, comparable to the 3-D visualization design of the first experiment. Groups of 3-D visualization and different input designs and interaction were investigated.

Modifications: The second experiment was designed according to the following concerns resulting from the first experiment.

First, in the first experiment, the visualization of the steel belt distance was realized as a surface plot. Further analysis showed that it was difficult to understand the distance as thickness of the material processed between the steel belts. Therefore, the surface plot was modified. The additional implication of the height in the distance diagram (underneath the plot) was used as the indicator for material thickness, which decreases during the process (see Fig. 5).

Second, for further investigations of the effect of 3-D in process control, the previously used input panel was substituted by a 3-D input panel.

During development of the 3-D data visualization, the input design of the process control task was a 2-D input form with buttons for the production process sections and each side of the plant. In critical situations, corrective inputs were made by button click on the corresponding deficient section and side. During the first experiment, uncertainties about the right side for corrective reaction were observed.

Therefore, a 3-D input panel with the same characteristic as the data visualization was developed. Deviations from normal process values were indicated by changes of form and color,

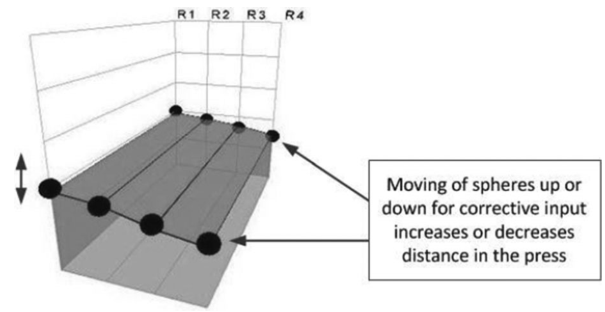

Fig. 6. Three-dimensional input panel (moving small spheres for corrective inputs).

emphasizing deviations requiring the operator's input. When a critical situation occurred, only a click on the critical section was required to display this section in a separate input panel where corrections could be made by direct manipulations on the selected section. Therefore, small spheres indicating press cylinders on each side could be moved up or down depending on process deviation and associated counteraction (see Fig. 6).

Resulting changes were immediately observable in the data visualization diagram, which enables the adjustment of process parameters as required for the normal press process. For additional corrective changes, another section could be selected by click.

A. Hypotheses

State-of-the-art literature referring to the visual momentum [19] and to the PCP supporting human information processing [9] as well as the results relating to perceived time pressure and observed error rates from the first experiments indicated that usage of 3-D for visualizations and input panels were expected to increase performance. This should result in a lower error rate and a shorter reaction time in the process monitoring task compared to 2-D input panels, because cognitive orientation and integration is not required. Furthermore, it was assumed that interaction (change of viewpoint) is not perceived as a secondary concurrent task. In contrast, interaction was expected to be additionally beneficial in 3-D input conditions requiring a sufficiently short reaction time and resulting in a low error rate. Providing 3-D visualization and input was expected to lead to an experienced mental workload on a medial level compared to different dimensionalities in visualization and input. The following hypotheses were stipulated.

(H2.1) Three-dimensional visualization and 3-D input panel compared to 2-D input panel lead to lower error rates and reduced reaction times.

(H2.2) Interaction is a beneficial factor in 3-D input conditions (low reaction time and low error rate).

(H2.3) Three-dimensional visualization and 3-D input lead to medial experienced mental workload.

B. Method

1) Participants: Twenty-eight persons (23 males, 5 females) aged 18–29 (M = 23.42, SD = 3.271) participated in the study.

TABLE IV
PARTICIPANT DOMAIN BACKGROUND

Domain	Number of participants
Computer science	8
Mechatronics	8
Mechanical engineering	7
Further technical education	2
other	3

TABLE V
EXPERIMENTAL GROUPS

Group 1 2-D input plus interaction	Group 2 3-D input without interaction	Group 3 3-D input plus interaction
Nine participants	Ten participants	Nine participants

Eleven participants were employees of a university and 13 were students from different domains (see Table IV). Twenty-seven participants indicated prior experience in 3-D applications, predominantly through games.

2) Experimental Design: In the second experiment, a between-design of data visualization and input design (see Table V) was examined in three groups (random assignment).

The input design was realized in 2-D consisting of sliders for each press cylinder and 3-D as described above. Data visualization was realized in 3-D for all groups.

Four different complex problems with specific characteristics in deviation from the normal process were simulated. Each group received the same problems; only the input panel and the possibility to interact were different. Ten critical and two noncritical/normal situations occurred during the whole process simulation task. In critical situations, early and adequate intervention through corrective input was to prevent material scrap. Problems arose at different sections of the press and developed dynamically. For example, one problem slowly occurred during material inclination; another problem resulted from (a simulation of) incorrectly set parameters in the press. Not every small deviation developed to a problematic situation. Noncritical situations did not require any reaction.

Corrective input was possible as long as the material was in the press. In contrast to the first experiment, control of material inclination was not possible. For effective regulation of the process in the press (changes of distance parameter), corrections were to be done in the early section of the press, where the material is still thick and loose and thus easier to influence. In advanced stages of the process, regulation is harder as the material is more compressed, making changes in distance through adjustment of pressure less effective.

During the monitoring task, interaction with the 3-D diagrams was possible (groups 1 and 3). Like in experiment 1, mouse input allowed for freely choosing a viewpoint on each diagram. Additionally, for all groups, several sections could be zoomed in by using the mouse wheel, allowing selected areas to be monitored in detail.

3) Procedure: The procedure of the second experiment was comparable to the first. It was again divided into three sections: training, test, and final experimental section.

a) Training section: At the beginning, the functionality of the press as well as characteristics of specific problems and the appropriate correction inputs were presented in an audio–visual guide. After each problem presentation and the explanation of corrective input and the use of interaction and slider (only for problem exploration), the participants were given the chance to explore the particular problem by slider and 3-D interaction (if available for this group). In the next step, the participants' mental models of the press and the production process were compiled by card sorting of the normal press process using labeled cards, grouped by processes, states, and components. An interview followed, gathering the verbal description of the mental model (sorted cards) by the participant. Additionally, relatedness ratings were used to collect the participants' knowledge about problem characteristics. After measuring the participants' mental models, an audio–visual presentation summarized the problem characteristics in an overview. The training phase ended with a monitoring task (similar to the test phase), where detailed feedback was provided, concerning the correctness of the reaction time, the kind of corrective input, and additionally the problem name.

b) Test section: The ensuing test phase included the monitoring of the continuously working production process, which was interrupted unexpectedly and the screen was blanked (freeze point) several times to measure the current affective state [42] and situation awareness [43], [44] of the participants. In contrast to the first experiment, in the second experiment, the problem situations were simulated continuously, i.e., the subjects were able to observe the effects of their corrective inputs.

During the process control task, a secondary task was given, consisting of simple mathematical calculations, for which paper and pencil were provided.

c) Final experimental section: The final section consisted of questionnaires about mental workload, presence [25], and self-efficacy [45]. The whole experiment took about 180 min without any breaks.

4) Measurements[1]: Like in experiment 1, the reaction was measured by signal detection theory (hits, errors, false alarms, and correct rejections); reaction time concerns the reaction time for hits (difference in time between the appearance of critical situation and the corrective input, see experiment 1). Mental workload was gathered with the questionnaires already used in experiment 1.

C. Results

(H2.1) Three-dimensional visualization and 3-D input panel compared to 2-D input panel lead to lower error rates and reduced reaction times.

The data analysis is comparable to the first experiment. An error analysis showed a high overall error rate (60.16%) (see

[1]Furthermore, measurements of situation awareness, mental model, affect presence, and self-efficacy were applied.

TABLE VI
ERRORS AND HITS IN THE EXPERIMENTAL GROUPS (ALL PARTICIPANT REACTIONS)

	Errors	%	Hits	%
2-D input plus interaction ($N = 9$)	70	78.7	19	21.3
3-D input without interaction ($N = 10$)	55	56.1	43	43.9
3-D input plus interaction ($N = 9$)	45	52.3	41	47.7

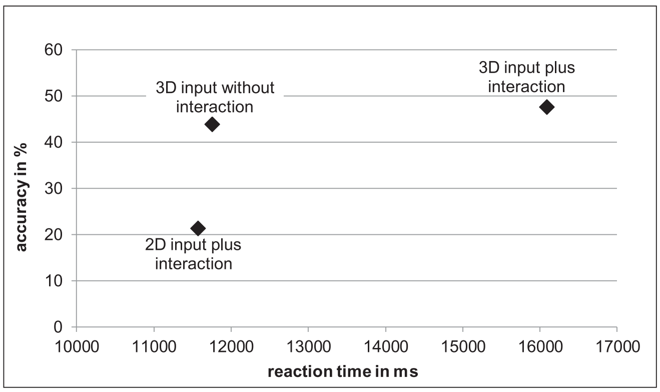

Fig. 7. Relation between accuracy and reaction time (speed–accuracy tradeoff).

Table VI). There is a significant main effect (chi-square = 9.254, df = 2, p = 0.01) and the 3-D input with interaction has the lowest mean (M = 12.393, SD = 1.873).

Examination of accuracy in problem detection and the reaction time for corrective inputs revealed a speed–accuracy tradeoff similar to the first experiment. The highest accuracy and lowest reaction times were achieved by the group using 3-D input without interaction, but the highest problem detection rate with larger average reaction times could be reached by the group using 3-D input with additional interaction (see Fig. 7). However, statistical analysis did not show a significant difference in reaction time ($U = -1.388$, $p = 0.165$) (H2.1).

Furthermore, a nonparametric analysis confirmed that hits and reaction time depend on experimental condition. Chi-Square indicated a main effect (chi-square = 9.254, df = 2, p = 0.01) and 3-D input with interaction achieved the highest accuracy (M = 12.393, SD = 1.873), but simultaneously the longest reaction time (chi-square = 7.943, df = 2, p = 0.05; M = 48060.357, SD = 36210.455). Considering 2-D input and 3-D input, both combined with interaction, showed significant differences in accuracy (U = −2.827, p = 0.005) (H2.2).

(H2.3) 3-D visualization and 3-D input lead to medial experienced mental workload.

Mental workload analysis showed no significant differences between the groups. On a descriptive level, the lowest mental demand was found in the group using 3-D input without interaction (M = 6.905, SD = 3.286), followed by the group with 3-D input plus interaction (M = 7.739, SD = 2.499). The highest effort was perceived in the group using 3-D input plus interaction (M = 8.461, SD = 1.889), where also slightly more problems were detected than in the group using 3-D input without interaction, where the lowest effort was experienced (M = 6.200, SD = 3.898). Furthermore, the perceived time pressure was comparable for both 3-D input conditions (3-D without interaction: M = 7.580, SD = 2.864; 3-D with interaction: M = 7.406, SD = 1.642; see Fig. 8). However, the differences in 3-D conditions according to mental demand ($U = -0.286$, $p = 0.76$) and effort ($U = -0.982$, $p = 0.33$) were not significant.

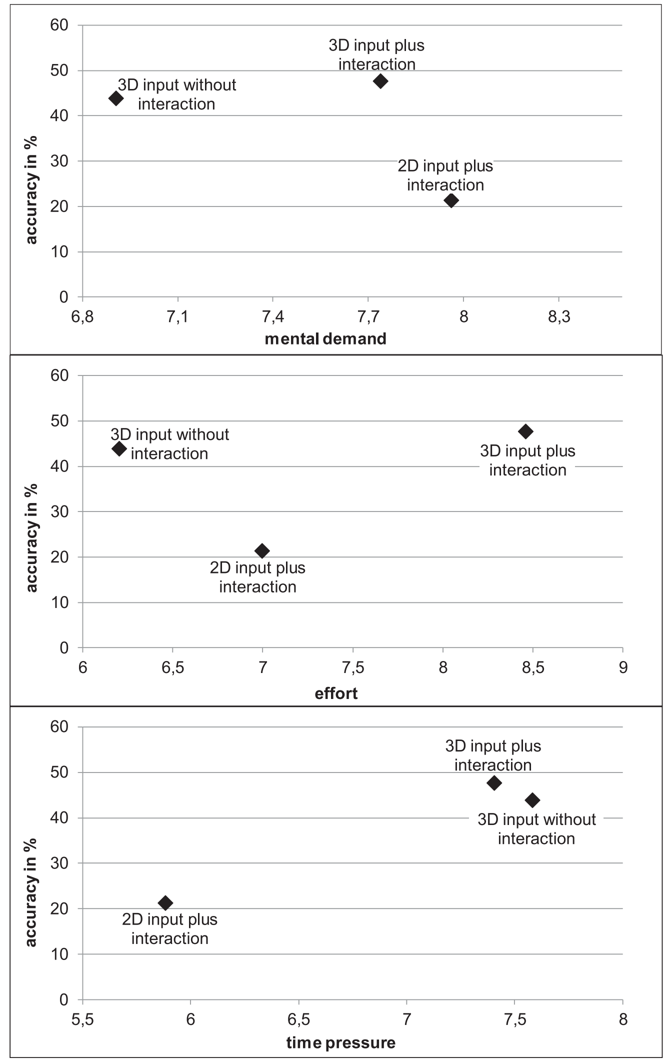

Fig. 8. Relations of accuracy and several mental workload scales (mental demand, effort, and time pressure).

Summarizing, the results of the second experiment indicate that the usage of 3-D input and the possibility to interact with data diagrams possess beneficial properties in terms of problem detection for process control task, which supports H2.1 and H2.2 partially. No differences in mental workload were found (H2.3). It can only be confirmed that the 3-D input panel leads to a significantly higher problem detection compared to 2-D input panel. Furthermore, added possibility of interaction slightly increases the accuracy of process control, but leads to an increased effort and mental demand on a descriptive level. Overall, 3-D input and interaction improves accuracy.

The additional third dimension in the input panel emphasizes the correlation of stimuli and response [4], [16]. The 3-D input panel is mapped onto the 3-D visualization, increasing performance in terms of the accuracy of corrective inputs in the process control task. The location compatibility [2] of 3-D visualization and 3-D input panel facilitates the alignment for corrective inputs. However, we did not find great quantities for differences in mental workload as expected.

VI. Discussion of the Results

Both experiments investigated, whether 3-D visualization and interaction can ease problem detection in process control tasks. In the experiments, interaction was studied by freely selectable viewpoints through rotating the diagram. The results of the first experiment show that 3-D visualization with interaction achieved the highest problem detection rate, accompanied by a medial reaction time and a medial time pressure. In the second experiment that mainly extended the usage of 3-D in the process visualization for input panels and examined it by regarding interaction through the possibility of changing the viewpoint, highest accuracy was achieved by the usage of 3-D input with the possibility of interaction, too. Usage of 3-D without interaction as well as 2-D input with interaction showed lower accuracy. This time we did not find any statistical significance for observed differences in reaction times and mental demand which might be due to the circumstance that the highest time pressure in the first experiment was experienced with the 2-D freeze image condition. This kind of experience was not realized in experiment 2. The data resulting from the tasks performed alongside the monitoring task were not analyzed, as these secondary tasks were merely included to simulate a situation similar to real work tasks.

Concluding from results of both experiments, problem detection was facilitated by using 3-D visualizations with the possibility to interact with the presentation. A general benefit of 3-D visualization in the process control could not be indicated. For the application example (experiment 2), performance in terms of accuracy was increased through the possibility to interact with the 3-D scene, but the reaction time was not improved. However, the lack of statistical significance concerning reaction times can also be due to the tradeoff between accuracy and speed. In this sense, it is a critical and positive factor that reaction times are not significantly higher when errors are reduced.

Both experiments showed high error rates, presumably due to the complex nature of the problem situations in combination with brief training of subjects with minimal experience in the field of the application example. Nevertheless, the use of 3-D visualization, especially including the possibility of interaction, reduced error rates and thus exhibited usefulness for process control tasks. Yet, with our experimental procedure, these findings could not be sufficiently operationalized.

VII. Conclusion and Outlook

The main contribution of this paper is to present empirical research on the question: How can the operator be supported in his/her task to observe, integrate, and interpret process information and to accordingly select the appropriate input parameter settings for the process control system in a specific process control task?

We focused on a specific class of technical processes, i.e., processes with the necessity of operator intervention to adjust process and machine parameters, but without a rigorous mathematical model. The chosen application example, a continuous thermohydraulic press, was selected for two empirical experiments: the first one focused on visualization, while the second one regarded visualization in combination with input. Regarding process control, 3-D visualization showed no general benefit. Yet, problems with increased complexity regarding the interdependence of process parameters benefit from integrated visualization in 3-D and support the operators' task. Both experiments showed that interaction in terms of 3-D rotation of 3-D process visualizations is beneficial for the correct detection of problems. Combined with 3-D input, interaction further increased the accuracy. The results lack in clarity for the benefit of a combination of both 3-D input and interaction. More investigation is needed to examine the combination of interaction and 3-D input.

In the experiments described before, only the rotation of the charts was used to interact with the visualization. Other forms of interaction, such as zooming or moving the diagrams on multitouch displays or even on mobile devices using input gestures, need to be investigated for their suitability for the use in process control. For mobile devices, such as tablet PCs or smartphones, close attention needs to be paid to varying display sizes. In these situations, the problem is not confined to how the data are displayed (2-D or 3-D), but needs to be extended to what kind of data is presented. Only porting the visualization on mobile devices does not solve the problem of information representation. Appropriate methods for information aggregation must be found for supporting the operator in process control. In further projects, the applicability of wearables like smart glasses, smart watches, or smart gloves as new input and output devices in industry will be investigated.

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