ERGONOMICS, 2003, VOL. 46, NO. 1–3, 19–40

Development of error-compensating UI for autonomous production cells

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Keywords: Autonomous Production Cells (APC); Flexible Manufacturing Systems (FMS); User Interface (UI); Human errors.

This contribution deals with the impact of human error on the overall system reliability in flexible manufacturing systems (FMS). Autonomous production cells are used to illustrate an error-compensating system design on the basis of Sheridan's (1997) paradigm of supervisory control. In order to specify human errors and their effects in terms of system disturbances, a taxonomy of system disturbances is recommended. This taxonomic approach was derived by a value benefit analysis and is based on HEDOMS (Human Error and Disturbance Occurrence in Manufacturing Systems) with slight modifications and Reason's GEMS (Generic Error Modelling System). The taxonomy is used for data acquisition. Next, a risk priority equivalent to FMEA (Failure Mode and Effect Analysis) is introduced to structure the data according to their relevance. Then, Vicente's and Rasmussen's guidelines (1987) for an ecological interface design are related to the paradigm of supervisory control. On the basis of these guidelines four case studies are presented to show their successful applicability for interface design in FMS.

1. Introduction

Since Adam and Eve human errors play a dominant role in human life: picking the apple and tasting it was a mistake with severe consequences. Violating intentionally pre-set rules, being aware of possible consequences, but underestimating their possibility or probability seems to be a basic characteristic of human motivational structure in terms of willingness to achieve possibly seducing effects with dubious side effects when performing a task. A human being with the strong will to perform perfectly, with a far-sighted horizon of awareness of consequences of action, and with visions about the 'right' directions in our discipline is the person honoured in this special issue of *Ergonomics*: Gavriel Salvendy, to whom we dedicate this manuscript on the occasion of his 65th birthday. His collected edition *Design of Work and Development of Personnel in Advanced Manufacturing* (Salvendy and Karwowski 1994) helps us in a unique way to understand the interplay of modern work system components and resulting effects on organization, technique and personnel. According to the operator's role as a planner and scheduler in supervisory control Nakamura and Salvendy (1984) stress human strengths and limitations in

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0014013021000040446

task performance within FMS, which is essential background information to understand the surrounding context of human error in this field of application. As is commonly known FMS possess a high degree of flexibility and finishing accuracy. Owing to technological and economic reasons system reliability is regarded as a determining success or failure aspect of a manufacturing organization.

However, system reliability is not only affected by technical aspects, but also influenced even more through undesired human errors. With respect to FMS a lot of studies were carried out in order to investigate the different causes of system disturbances. Summarizing these results, disturbances can be traced back to the following causes: (1) design errors; (2) component errors; (3) human errors; and (4) external factors (Kuivanen 1990, Döös and Backström 1993, Järvinen *et al.* 1996, Vannas and Mattila 1996). Similar causes were found by Majchrzak (1988). Allowing for human errors (~20%) and design errors (~30%) in terms of Reason's (1990) latent errors, there is a great potential for system improvement.

Consequences of such system disturbances can be interpreted in terms of safety or production aspects. For example, consequences of disturbances in the field of manufacturing are: loss of time, reduction of quality, production disruption and accidents (Zimolong 1990). It is therefore one important objective in developing FMS to provide mechanisms for reduction of the human error impact on system reliability. According to this an error-compensating approach of FMS will be presented in terms of a case study referring to Autonomous Production Cells (APC).

2. APC as a work system

Autonomous Production Cells are still in a state of basic research (figure 1) and are based on effective interaction of highly skilled operators as well as complex CNC-based machinery and industrial robots linked with an automated materials handling system. Its operation is controlled through a supervisory computer (Pfeifer *et al.*

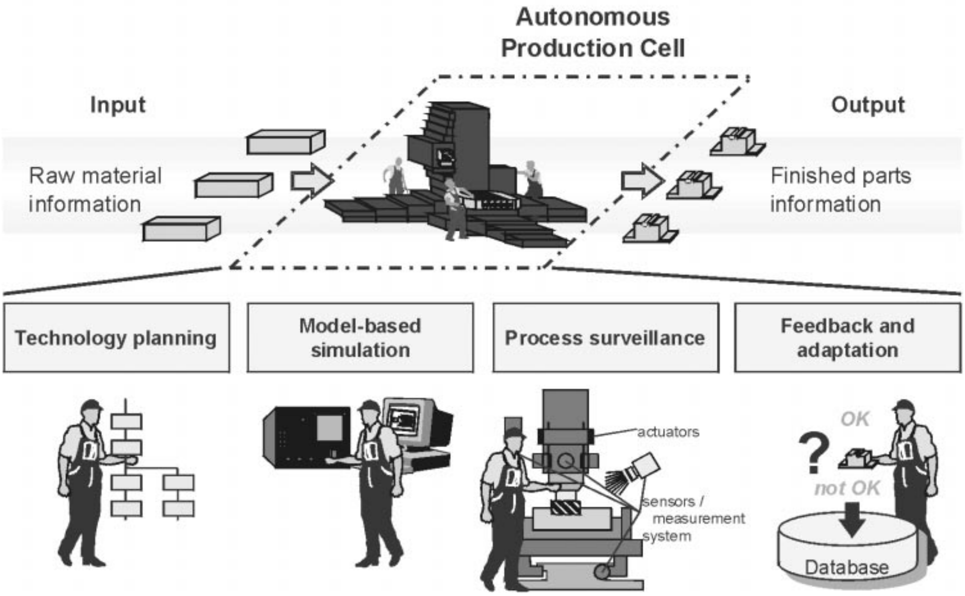


Figure 1. Autonomous Production Cell as a work system.

2000). An APC that is very closely related to FMS is dedicated to a single part family, so that each part family can be completely produced within the cell, and surrounding cells have minimum interaction with each other. Consequently APC have three design criteria.

(1) Operators and technical subsystems are an autonomous organizational unit of the living organism of the production plant.
(2) Operator's tasks of planning, set-up, numerical control programming, process control, quality inspection and fault management are locally integrated in the manufacturing cell.
(3) Mainly independent execution of complex processing steps with a high degree of undisturbed functioning is striven for.

The technologies of 5-axis milling and 3-D laser welding have been chosen as exemplars, as they are of industrial relevance and as they require complex mechanisms for process control.

3. Human error in supervisory control

In order to understand human errors in industrial manufacturing a concrete definition of human error (HE) is needed first. In the literature a lot of definitions concerning HE can be found. Our definition is mainly based on Reason (1990: 9):

> Thereby a human error is defined as an execution respectively non-execution of a planned sequence of mental or physical activities, which can run the system by crossing determined accuracy limits to an undesirable system state. Additionally it is assumed that no other error promoting work system components are involved.

This definition also stresses the interplay of the human operator and other work system components, as the label HE is often used to imply responsibility and blame. Rasmussen (1987) has a similar understanding of HE when using the term *person-machine system flaw*. Park (1997) accounts for three reasons why people err: (1) task complexity, (2) error-likely situations in terms of poorly designed work situations, and (3) human behavioural characteristics. To design accurate and human-centred work systems one has to keep these different reasons in mind.

What does this mean to APC? According to Schlick *et al.* (2002) APC support the paradigm of supervisory control. Thus, supervisory control means one or more human operators are setting initial conditions for intermittently adjusting and receiving information from a computer that itself closes a control loop in a well-defined process through artificial sensors and effectors (Sheridan 1997). The operators' task spectrum can be mapped to Sheridan's specific human supervisory functions, whereupon operator tasks do not only include monitoring tasks, which can cause vigilance problems, but also essentially planning, intervening and learning tasks in APC (Schlick *et al.* 1999). Thus, human computer interaction (HCI) plays a dominant role in process control depending on the degree of automation. It is up to the system designer to provide a well suited human interactive user interface in APC. Having this in mind, Sheridan (1997) distinguishes ten levels of automation in human-computer decision making, which the system developer should consider carefully. On the one hand, the operator should be unburdened from routine tasks, on the other hand he may be so far away from the real process, which Bainbridge (1987) indicates so accurately as *irony of automation*. This is even more of a paradox as system designers try to ameliorate these effects of automation, e.g. at the skill-based level by using force feedback devices in human-computer interaction.

The central leitmotif in developing APCs is expressed by the third design criteria of APC trying to achieve nearly trouble-free production. In general, being trouble-free in terms of human error reduction in APC can be approached in two ways: (1) elimination of the human impact on critical system functions, or (2) provision of an error-compensating user interface design. For this, a framework is needed which relates the paradigm of supervisory control to human information processing and thereby to human error, as human errors can be interpreted as a 'window to the mind' (Norman 1979). A well-known framework is proposed by Sheridan (1997), which can be seen in figure 2. Therefore, the goal is to produce meaningful representations of cell processes that simultaneously support all levels of information processing by Rasmussen (1986), namely skill-based, rule-based and knowledge-based (SRK-based).

According to this framework human errors can take place at different levels of information processing. With respect to his SRK model Rasmussen (1986) distinguishes three kinds of error: (1) skill-based, (2) rule-based and (3) knowledge-based errors. Their external form such as omission, wrong timing, etc. (Swain and Guttmann 1983) has a direct impact on the controlled process in terms of manual control or an indirect impact in terms of semi-automatic or automatic control, e.g. coded NC programme. It is up to the user interface design supported by appropriate computer aid to limit or compensate these negative effects.

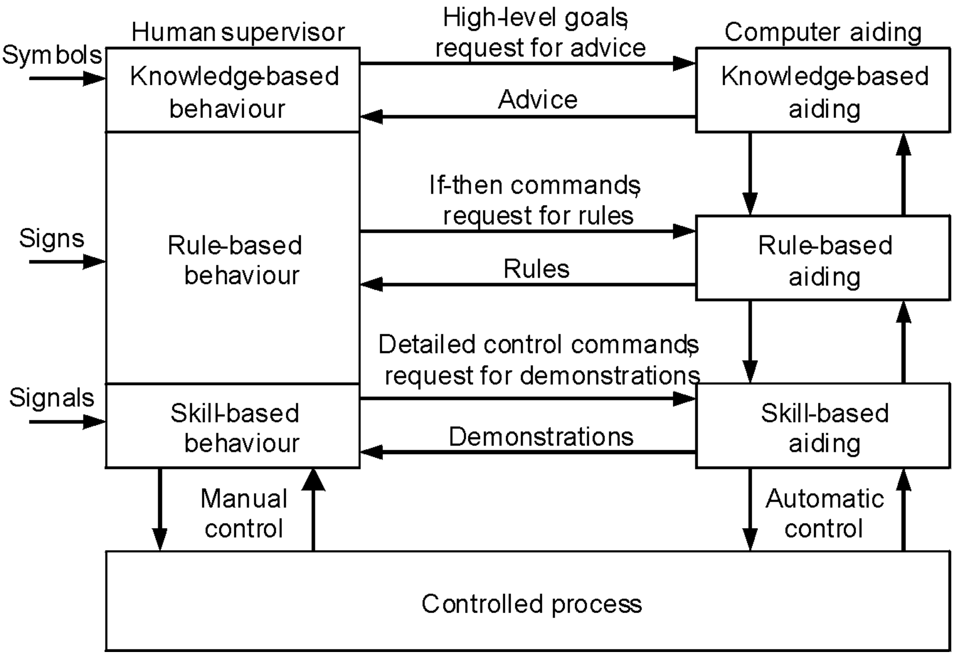


Figure 2. Supervisor interactions with computer decision aids at knowledge, rule and skill level.

Consequently, in order to realize an error-compensating user-interface design the whole chain of error causes and consequences has to be known. In general, human error can be approached from two viewpoints: prospective and retrospective (Park 1997). Both approaches can still be used for classification of human error as an important tool for the purpose of qualitative diagnosis and decision support in user interface design. Thus, a structured taxonomy of human errors is needed, which results especially from software developers' needs in APC in general.

According to the application domain, the following primary requirements for a data structure of human error and its consequences should be taken into account. First, information concerning the deeper root cause(s) is needed, so it can be cleared up, whether the phenomenon has either a technical, organizational or personnel origin. Second, as far as human beings are concerned, their initial failure mechanisms are of special interest. Third, the knowledge about intentional violation of organizational or safety rules is of great concern (Salminen and Tallberg 1996). Fourth, a specification of consequences in terms of safety and, fifth, consequences in terms of production have to be considered. Sixth, an occurrence rate or a human error probability should be available. Seventh, necessary recovery strategies are required. Beyond these criteria, there are (8) objectivity, (9) wide spread of application, (10) applicability, and (11) integrated software support as criteria of utility.

4. Evaluation and synthesis of classification approaches

In the literature a lot of taxonomies for human error classification can be found. A survey is given in Park (1997). Seifert (1992) distinguishes three supersets of taxonomic approaches: (1) occurrence-oriented, (2) cause-oriented and (3) combined approaches. As not all taxonomies are of the same relevance regarding application in APC, a subset of the most important representatives was discussed. Thus, a cross-section regarding the three subsets was formed: Rigby (1970), Rouse and Rouse (1983), Swain and Guttmann (1983), Rasmussen's Multi-Aspect Taxonomy (1986), Hacker (1987), Seifert and Brauser (1987) and GEMS—Generic Error Modelling System by Reason (1990). Additionally, the newly developed methodology named CREAM (Cognitive Error Analysis Method; Hollnagel *et al.* 1999) was taken into account, as it is a so-called second generation HRA technique (Human Error Analysis) stressing cognitive demands in task performance. At least, HEDOMS (Human Error and Disturbance Occurrence in Manufacturing; Barroso and Wilson 1999) and FMEA (Failure Mode and Effect Analysis; QS-9000 1999) were regarded as they were especially designed for industrial manufacturing purposes.

According to the different criteria of choice a value benefit analysis was carried out. This value benefit analysis was based on multi-attributive functions (Eisenführ and Weber 1994) with respect to the different criteria of choice. Thus, each criterion was evaluated using a three-stage scale, whereupon the first rank 'requirement fulfilled' had a value of 1, the second rank 'requirement only in part fulfilled' had a value of 0.7, and for the third rank 'requirement not fulfilled' a value of 0 was assigned. The objective of evaluation was to find an approach that fits best.

The results can be seen in table 1. Obviously, no taxonomic approach fulfils all requirements. HEDOMS, FMEA and CREAM fit best, whereas the third criterion of choice: 'Intentional violations of rules' is completely lacking. GEMS is the only approach that explicitly regards intentional unsafe acts in detail. Thus, a synthetic

Table 1. Results of value benefit analysis with respect to different taxonomies of human error.

	Criterion/Method	Rigby (1970)	Swain and Guttmann (1983)	Hacker (1987)	Rasmussen (1986)	GEMS (Reason 1990)	Rouse and Rouse (1983)	Seifert and Brauser (1987)	CREAM (Hollnagel *et al.*, 1999)	HEDOMS (Barroso and Wilson 2000)	FMEA (QS-9000 1999)
1	Root cause (technical, organisational, human)	○	◐	○	●	○	○	●	●	●	◐
2	Human failure mechanism	◐	●	●	●	●	●	●	●	○	○
3	Intentional violations of rules	○	○	○	○	●	○	○	○	○	○
4	Consequences in safety terms	○	○	○	◐	○	○	◐	◐	●	●
5	Consequences in production terms	○	○	○	◐	○	○	◐	◐	●	●
6	Human error probability	●	●	◐	◐	◐	◐	◐	●	●	●
7	Provision of recovery strategies	◐	○	○	○	○	○	◐	◐	●	●
8	Objectivity	●	●	◐	◐	◐	◐	●	●	●	●
9	Wide spread of application	◐	●	◐	◐	◐	◐	○	◐	◐	●
10	Applicability	●	●	◐	◐	●	◐	◐	◐	●	●
11	Integrated software support	○	●	○	○	○	○	○	◐	●	●
	v_i (not weighted)	0.46	0.61	0.35	0.56	0.46	0.35	0.59	0.75	0.79	0.79

● = requirement fulfilled;
◐ = requirement only in part fulfilled;
○ = requirement not fulfilled.

framework, consisting of GEMS and HEDOMS, is recommended as they fulfil in sum all requirements. Although CREAM and FMEA received similar ratings, HEDOMS was chosen as it is especially designed for FMS.

Integrating HEDOMS and GEMS one has to keep in mind the concept of disturbances (human errors are only a subset of system disturbances) that takes account not only of causal factors but also consequences in both safety and production terms. As HEDOMS distinguishes direct and root cause in disturbance recording, there are parallels to Reason's (1990) active and latent failures. Latent failures aren't assigned only to the operator, but also to prior levels of work system design or organizational failures. This phenomenon is also stressed in our core definition of human errors by the phrase 'assuming that no other error-promoting work system components are involved'.

Thus, a few modifications are recommended. First, the direct cause for disturbance occurrence in HEDOMS has been substituted through an affiliated approach to first order work system disturbances based on Kirchner's (1997) definition of work system components. Following on, each class can have two distinct states: (1) production factors are missing, or (2) defective or inadequate production factors.

Second, the class 'insufficient operator' has been enlarged according to Reason's (1990) unsafe acts (see GEMS). Following this, the class consists of a broad category encompassing (1) operator not available, (2) slips/lapses, (3) rule-based mistakes, (4) knowledge-based mistakes, and (5) violations. Besides, according to Sheridan's (1997) model of computer aid (figure 2), Rasmussen's distinction in SRK errors holds up as shown above.

Third, in order to stress the cognitive processes, it is essential for the design phase to know which psychological error mechanisms are involved. Consequently, the root cause in terms of human error is adapted to GEMS failure modes such as inattention, misapplication of rules, etc.

Fourth, each disturbance is related to the context in which it takes place. This context mainly depends on the operator's task spectrum. Thus, from the prospective point of view, the task analysis is a crucial step in designing new systems (Luczak 1997). From the retrospective point of view there must be a situational awareness, which can be used for data recording.

The overall structure adopted for analysis in human error and its consequences in terms of system disturbances is shown in figure 3. This will be the formal basis for an error-compensating user-interface design.

5. Data recording

In order to identify human errors and their consequences for UI design, it is important to know in which context they can appear. Thus, data recording was based on the process chain: technology planning, model-based simulation, process surveillance, feedback and adaptation (figure 1). As APC are in a state of basic research and no real application exists the process chain was specified using prospective task analysis. Campion and Medsker (1992) define task as a set of actions performed by a worker that transforms inputs into outputs through the use of tools, equipment, or work aids. Two task models for APC were derived by decomposition using graphical representation techniques as there is one for 3-D laser welding and one for 5-axis milling (Reuth *et al.* 2001a). Nevertheless best results can be achieved through the integration of so-called 'lessons learned', which can be used

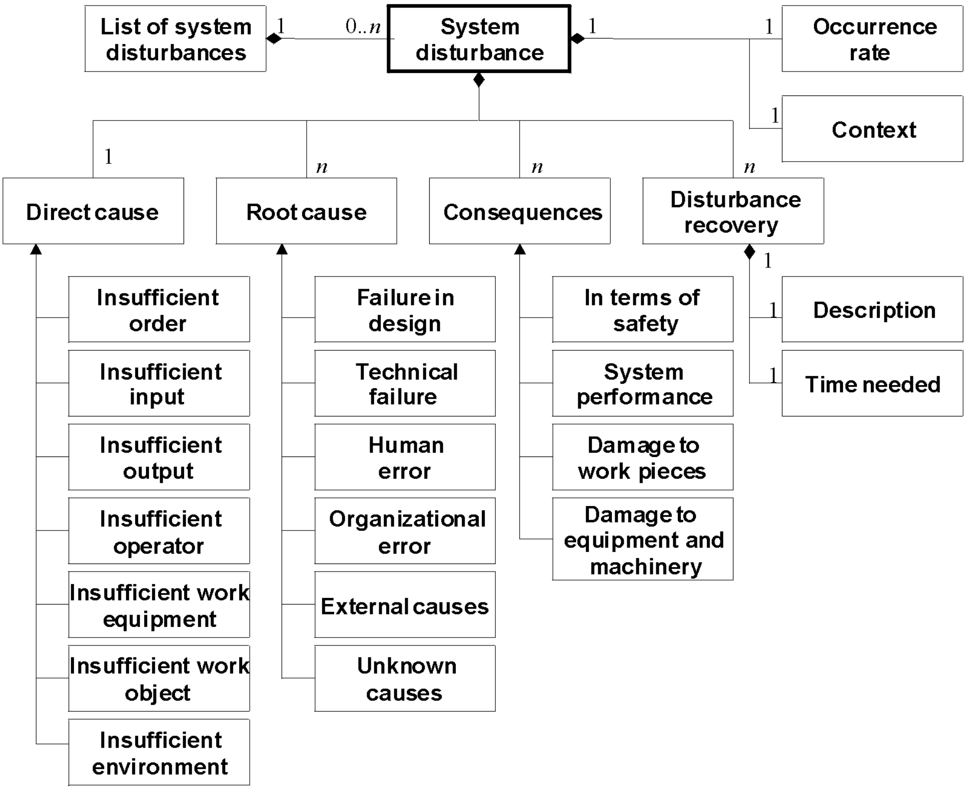


Figure 3. Structure on human error analysis in terms of system disturbances based on UML (Unified Modeling Language; Booch *et al.* 1998).

to avoid similar prior design failures. Therefore, two corresponding task networks in conventional manufacturing (3-D laser welding and 5-axis milling) have been developed by literature analysis, expert enquiries and video observation (Reuth *et al.* 2001a).

Specific details of task elements for all four task models were acquired with support of a questionnaire, which referred to an underlying 3-D laser welding order and a 5-axis milling order. The lot size of each manufacturing order was five parts. Two groups of raters participated in each technology. The first group consisted of APC experts. These experts were competent in narrow domains of the whole work process only. Therefore, the APC experts exclusively rated the subset of APC task elements that were compatible to their competency profile. The second group included experienced industrial workers in terms of conventional manufacturing technologies. These experts rated the attribute values of the whole set of task elements of the conventional manufacturing system (table 2).

First, each task was categorized according to the dominant level in Rasmussen's SRK model. Second, each task was specified to its supervisory function, whether the task is performed manual, semi-automatic or whether it is under automatic control. Third, in the case of semi-automatic or automatic control the rater was supported, during his reasoning about possible system disturbances, by first order causes of disturbances (figure 3). Fourth, once having identified possible system disturbances the rater had to specify the root causes and their consequences in safety and production terms. Fifth, an occurrence rate was needed. Sixth, the raters were asked for possible recovery strategies. Technical failures were disregarded as they were beyond the scope of this study. Finally, the relevant disturbance data was codified according to the proposed taxonomic approach.

6. Identification of problematic tasks

Owing to a large amount of data on human errors, the problem arises of where to start with measures for error reduction or error compensation in user interface design. This can be done subjectively on the basis of individual preferences and expertise through evaluation in the mind or the use of analytical decisions to help in terms of quantitative prioritizing. This is no new idea, as it has already been practiced in the FMEA as a function of occurrence rate (O_R), relevance and detection rate (D_R). Thus a risk priority equivalent (RPE) will be introduced to structure the problem field. The RPE is similar to the approach in FMEA, but it regards consequences both in safety (C_S) and production terms (C_P) explicitly (table 3). Thus consequences of production contain three sub-levels: affecting system performance (C_{PP}), extent of damage to material (C_{PM}) and extent of damage to equipment and machinery (C_{PE}). Beyond, it is possible to weight (n_{pp}, n_{pm}, n_{pe}, n_s) these factors according to analysers' needs. Consequently the RPE is directly linked to productivity, scrap rate, etc. and is therefore ideal for structured system improvement in terms of User Interface (UI) design. According to the detection (D_R)

Table 2. Description of acquisition of task attributes.

Technology	Work system	Number of experts	Average occupational experience
3-D laser welding	Conventional	5	6 years
5-axis milling	Conventional	6	15 years
3-D laser welding	APC	7	3 years
5-axis milling	APC	8	3 years

Table 3. Criteria of evaluation based on HEDOMS and corresponding ordinal scalars for RPE calculation (Notation: $C_{PE}=3$, personnel within company is able to correct it; $C_{PE}=4$, requires technical support from outside the company).

Safety level: system safety, C_S		Production level: system performance, C_{PP}		Production level: damage to material, C_{PM}		Production level: damage to equipment/machinery, C_{PE}	
No effect	1	No effect	1	No damage	1	No effect	1
Risk exists	2	Work conditions worsened	2			Minor damage	2
Minor accident	3	Work prevented (Single WP)	3	Material partially recoverable	3	Medium damage	3
Major accident	4	Work prevented (Multiple WP/Cell)	4			Major damage	4
Catastrophe	5	Work prevented (Whole company)	5	Materials non-recoverable	5	Recovery impossible	5

and occurrence rate (O_R), the same criteria of evaluation as in FMEA (from 1 (always) to 10 (never)) were applied for calculation of RPE.

$$RPE = O_R \cdot C_{PP}^{n_{pp}} \cdot C_{PM}^{n_{pm}} \cdot C_{PE}^{n_{pe}} \cdot C_S^{n_s} \cdot D_R$$

Applying RPE calculations a list of urgent system disturbances will result, which have to be considered in terms of appropriate error compensating interface design. According to this the top 5 relevant RPEs will be presented for each technology and work system (tables 4–7), whereas C_s was set to '1' as consequences in safety terms were beyond this study.

7. Guidelines for error-compensating UI design

In order to account for human errors in task performance, a human-centred system design is recommended. With growing investment in user interface design, a lot of design standards were established. In Europe, the German Institute of Standards has proposed a standard for user interface design: ISO 9241/10 (1996). Although a lot of work has been done in the field of usability engineering, the software designer is spoiled by the choices. Smith (1988) points out this dilemma in his paper: 'Standards versus guidelines for designing user interface software'. According to the designer's point of view guidelines are helpful and instructive, whereas standards are more restrictive and more formal. As APCs do not involve mass production, the use of guidelines seems to be useful due to its specific requirements.

The ecological interface design developed by Vicente and Rasmussen (1987) seems to be a promising approach to realize this error-compensating UI design. In order to identify those areas where design improvements are necessary, Vicente and Rasmussen (1987) focus upon four categories of error: (1) errors related to learning and adaptation, (2) interference among competing cognitive control structures, (3) lack of resources, and (4) intrinsic human variability. To increase system tolerance with respect to human errors, ten rules for improved system design are recommended (Reason 1990).

(1) Make the boundaries of acceptable performance at the skill-based level visible.
(2) Provide feedback to support functional understanding and knowledge-based monitoring.
(3) Use semantic cues for action in terms of signs and symbols not only as readily interpretable.
(4) Provide tools in case of system disturbances to develop possible recovery strategies offline.
(5) Use overview displays for process control.
(6) Reduction of 'procedural traps' (i.e. activation of strong but wrong rules) by giving integrated patterns as cues for action.
(7) Support memory with some externalized schematic in case of interference between possible competing mental models.
(8) To aid recovery from errors due to lack of resources, use the available data to present information that is simultaneously suitable for SRK-based processing.
(9) Set-up of informational structure in terms of an externalized mental model.
(10) Provide the user with external memory aids to support the retention of items, acts and data.

Table 4. Top 5 system disturbances in conventional manufacturing with respect to 5-axis milling.

System disturbance	Context	Direct cause	Root cause	C_{PP}	C_{PM}	C_{PE}	D_R	Recovery strategy	Occurrence rate	Occurrence number	RPE
Mistyping (wrong axis, etc)	NC = programming	Slip/lapse	Reversal	3	5	2	3	Undoing of mistyping	0.10000	8	720
Program failure	NC-program processing each G-sentence	Knowledge-based mistake	Problems with complexity	3	5	3	2	Correction of NC-program	0.02000	7	630
Program failure	NC-program processing with reduced speed	Knowledge-based mistake	Problems with complexity	3	5	3	2	Correction of NC-program	0.02000	7	630
Mistyping (wrong axis, etc)	Optimization of technology, gauge and process)	Slip/lapse	Reversal	3	5	3	2	Correction	0.05000	7	630
Program failure	NC-program processing	Rule-based mistake	Wrong application of good rule	3	5	3	2	Correction of NC-program	0.02000	7	630

Table 5. Top 5 system disturbances in APC with respect to 5-axis milling.

System disturbance	Context	Direct cause	Root cause	C_{PP}	C_{PM}	C_{PE}	D_R	Recovery strategy	Occurrence rate	Occurrence number	RPE
Clamping jaws in milling path	Planning of clamping	Knowledge-based mistake	Problems with complexity	3	5	3	2	New planning and clamping	0.01000	6	540
Adverse choice of working tools	Formation of alternative operation-features	Rule-based mistake	Wrong application of good rule	3	5	2	2	Select new working tool	0.02500	7	420
Wrong data set	Determination of tool and cutting material	Insufficient work equipment	Organizational failure	3	5	2	2	Proof and correction of database	0.02000	7	420
Wrong data set	Calculation of cutting limits	Insufficient work equipment	Organizational failure	3	5	2	2	Proof and correction of database	0.02000	7	420
Working tool at wrong location	Loading tool magazine	Slip/lapse	Reversal	3	5	2	2	Select right place	0.00300	6	360

Table 6. Top 5 system disturbances in conventional manufacturing with respect to 3-D laser welding.

System disturbance	Context	Direct cause	Root cause	C_{PP}	C_{PM}	C_{PE}	D_R	Recovery strategy	Occurrence rate	Occurrence number	RPE
Collision with clamping jaws	Input of end points of simple welding paths	Knowledge-based mistake	Problems with complexity	3	5	3	2	New planning of clamping	0.05000	7	630
Wrong choice of parameters	Calculate parameters by the use of spreadsheets	Knowledge-based mistake	Problems with complexity	3	5	2	2	New choice	0.05000	7	420
Wrong welding parameters	Teach-in/ programming	Rule-based mistake	Wrong application of good rule	2	5	1	2	Adaptation of parameters	0.50000	10	200
Slow down of axis in curves	Input of end points of simple welding paths	Insufficient work equipment	Failure in design	2	5	1	2	Change of parameters	0.90000	10	200
Inappropriate welding design	Definition of work process	Insufficient order	Failure in design	2	5	1	2	Contact with customer	0.50000	10	200

Table 7. Top 5 system disturbances in APC with respect to 3-D laser welding.

System disturbance	Context	Direct cause	Root cause	C_{PP}	C_{PM}	C_{PE}	D_R	Recovery strategy	Occurrence rate	Occurrence number	RPE
Cooling works incorrect	Verification of machinery state	Insufficient work equipment	Technical failure	3	5	2	3	Repair	0.03300	7	630
Collision of handling devices	Clamping	Insufficient work equipment	Failure in design	3	5	3	2	If necessary revised design	0.00050	4	360
Collision of handling devices	Unclamping	Insufficient work equipment	Failure in design	3	5	3	2	If necessary revised design	0.00050	4	360
Mistyping at parameterizing	Definition of work process	Slip/lapse	Reversal	2	5	1	3	New input	0.01000	6	180
Exceeding clamping force	Planning of clamping	Insufficient work equipment	Failure in design	2	5	1	3	Re-planning	0.00500	6	180

Guidelines (1) to (4) are directed at errors associated with the learning process. Guidelines (5) to (7) are concerned with mitigating the effects of human errors, which arise from interference among cognitive control structures. Guideline (8) and (9) are concerned with compensating for a lack of available cognitive resources. The final guideline seeks to minimize the effects of stochastic errors (Reason 1990).

However, these guidelines have to be related to the different levels of computer aiding (figure 2) in order to check whether all levels are regarded. This is simply shown in table 8. As it is shown, these guidelines mainly focus on the rule- and knowledge-based level in human information processing. This does not matter. In contrast, it can be considered to be an advantage as Schlick *et al.* (2002) could obtain a shift to higher cognitive levels in APC and therefore appropriate computer support at these levels is more valuable. Thus, these guidelines or 'Golden Rules' have to be tailored in terms of selection, interpretation and modification with regard to the specific sequence of human-computer interaction. Furthermore, tailoring is related to specificity (Shneiderman 1998). It is beyond controversy that guidelines can not take the place of experience when translated into specific design rules. This is even more apparent if some situations involve conflicting design guidelines. At this point the designer has to value which design principle violation has the fewest, negative consequences.

Finally, the software development process should be seen as an iterative process including analysis, design, implementation and evaluation. Therefore it is up to the software development team to care for testing the user interface in terms of usability and error compensating effects as well (section 9).

8. System improvement: some case examples

Summarizing the results (tables 4–7), four general problem areas can be identified: (1) as far as *NC programming* is concerned, human errors can be observed at the skill-, rule- and knowledge-based level; (2) these can result in *collisions* of machine-axis, clamping systems, etc.; (3) minor effects to system functionality can be expected by incorrect *tool handling,* in return severe consequences for product quality will follow; (4) the last field is strongly linked to the APC work system due to an integrated and automated *materials handling system*. Subsequently, these problems will be discussed in terms of system improvement by applying many of the 'Golden Rules' in user interface design. The reason for this is quite easy, as human information processing often switches between the different SRK levels. Therefore, it is necessary to support each level of human information processing by appropriate computer aid.

Table 8. Support of SRK-based computer aid by applying guidelines of an ecological interface design (Vincente and Rasmussen 1987).

	Guidelines									
	1	2	3	4	5	6	7	8	9	10
Skill-based aid	●				●			●		
Rule-based aid		●	●		●	●		●		●
Knowledge-based aid		●	●	●			●	●	●	●

8.1. *Use of semantic units in NC programming*

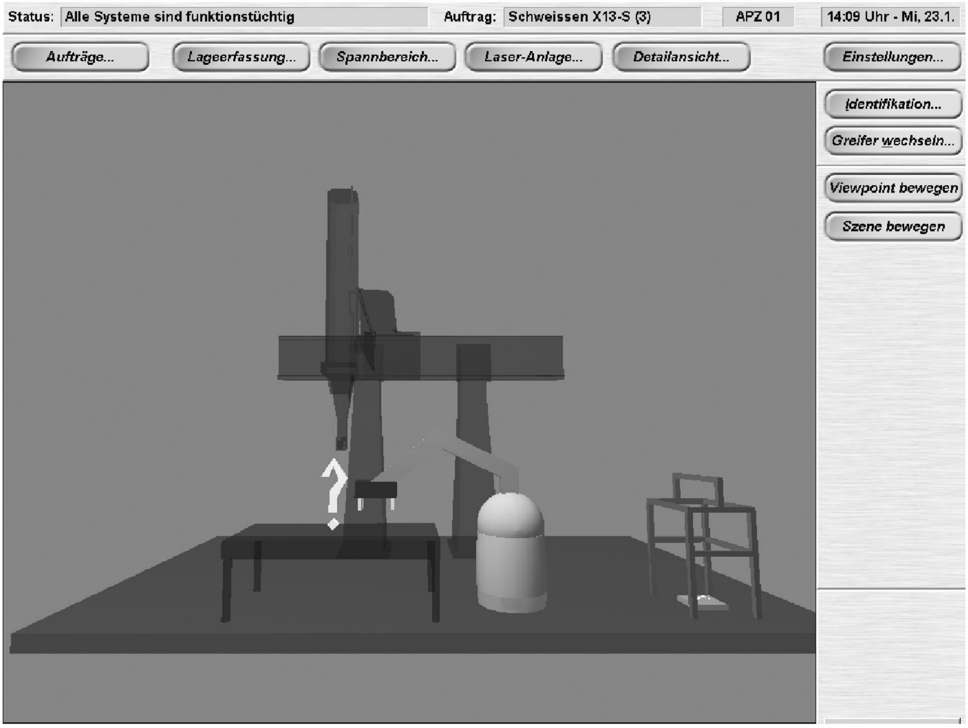
Conventional NC programs are coded in long listings of G-sentences not directly referring to an operator's view on the production task. Thus, the operator has to code his representation of working strategy in alphanumeric listings. Obviously this opens the door for mistyping (slips and lapses). Independently these listings stress the human being in information processing especially in terms of three-dimensional spatial orientation. APC, on the other hand, rely on a feature-based product data model integrating geometric (holes, pockets, etc.) and technological information of the product as well as planning results, which will be attached during the planning process. 'Features' are technical elements that describe the characteristics of a limited product area (Eversheim *et al.* 1998). A feature connects all information describing the shape of a partial product area with a semantic component, specifying, for example, technological attributes. By applying rule 9 these two aspects, shape and semantics, are combined into a cognitive compatible unit, which provides the user also with an external memory aid. This is reached by the use of innovative CAD/CAE techniques.

8.2. *Avoidance of collisions by process simulation*

Mechanical collisions of machine axis, clamping systems, etc. are the most undesired events in modern production units. Most of these collisions arise by knowledge-based errors, as humans are limited in their workspaces. However, system complexity causes problems in rational reasoning as humans in general tend to simplify. Thus, the operator proves his working strategy (coded NC programme) by operating the machine using the override either without tool or without work piece. Also, there are mechanical parts in progress which can impact upon each other. Therefore it is desirable to disconnect the verification of the NC programme from the actual machining system and to support the human with appropriate decision tools. This can be achieved by applying rules 2 and 4. Offline process simulation is not new at all. In Schlick *et al.* (2000) a virtual reality user interface is presented called Active-UI (Autonomous Production Cells' multi-modal and adaptive User-Interface). Active-UI has been designed for 3-D laser welding especially. The core of Active-UI is formed by the metaphoric principle as it depicts an exact geometric reflection of the APC and its processes on the shop floor (figure 4), wherein the operator has the chance to explore his planning. The following five tasks of the APC operator are supported by the following metaphors: (1) Set-up of robot and sensors; (2) selection of manufacturing order; (3) workshop-oriented simulation; (4) process control and monitoring; and (5) process diagnosis. According to the simulation of the manufacturing order (shows planning values over welding seam), this will be enriched by the clamping system in the near future. Consequently, it will be possible to detect any undesired possible impact of machine axis, work piece, work table and clamping system. These collisions will be reported to the operator by visual symbols and by the use of audio-feedback as well: 'Attention! Working strategy is not appropriate due to collision between <part xy>and <part yz>'. In addition, the fail-safe concept will be implemented, so that the machine cannot be started until correct re-planning takes place.

8.3. *Graphical tool handling and feedback control*

Inappropriate choice of tools is quite common even in modern production. Its appearance can take place in two different ways: (1) wrong coding of tools in NC



Status: Alle Systeme sind funktionstüchtig

Auftrag: Schweissen X13-S (3)

APZ 01

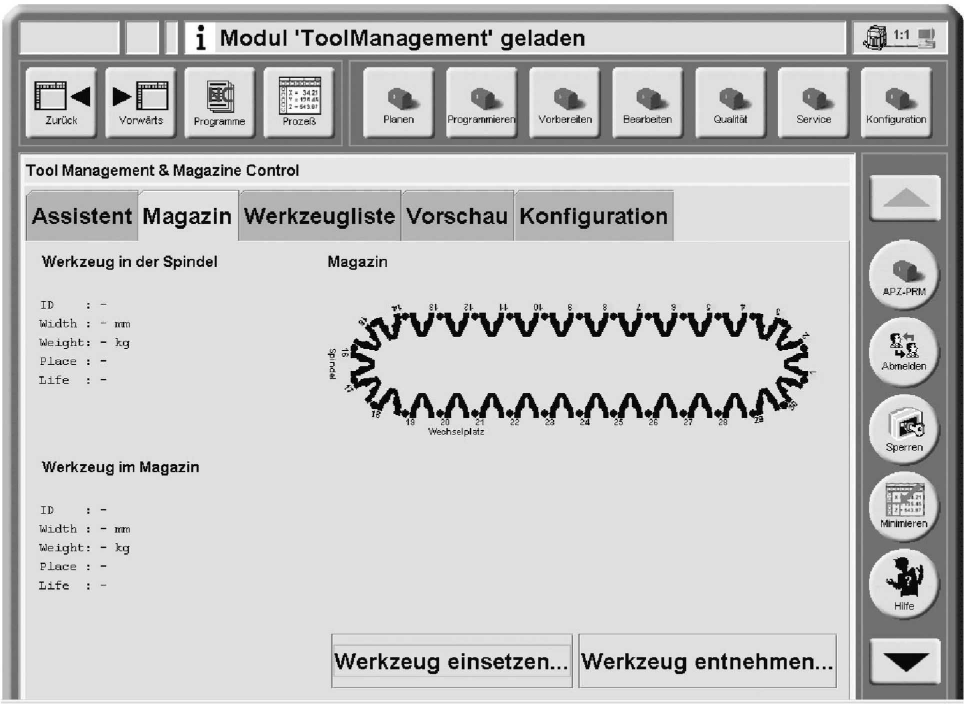
14:09 Uhr - Mi, 23.1.

Figure 4. Active-UI.

programming, and (2) wrong choice in machine set-up in terms of the tool magazine. According to this, human error mechanisms are mainly placed at the skill- and rule-based level. Having in mind that human variability is inevitable, mechanisms have been developed to control these failures by system and humans as well. First, the tool magazine setting in the APC machine control (each tool has its own magazine tool place) is presented to the operator in a graphical way as a memory aid. For this, he can load/unload a tool to the relevant tool place as it is required by the NC program (figure 5). The state of each tool place is represented by graphical symbols (black dot = tool loaded; white dot = no tool). In order to reduce mistyping in tool specification at the syntactical level, each tool is part of a process data model that is binary coded in a data bank. Consequently, a list of available tools including a pictorial representation is shown to the operator for selection. In order to prove electronic tool place assignment and physical tool place, it is recommended to use tools with a code bar, so that the system can identify them through the use of sensors. Thus, in case of non-correspondence between the tools, a failure message can be generated to support efficient recovery.

8.4. *Flexible handling system by operator experience*

Although the process of (un-)clamping is highly integrated and automated in APC, it reaches a high RPE, which is able to affect the whole cell in case of disturbances; remember the concept of Computer Integrated Manufacturing (Eversheim 1989). Thus, the system developer has to keep his overall objectives in APC in mind: high



Werkzeug in der Spindel

ID : -
Width : - mm
Weight: - kg
Place : -
Life : -

Werkzeug im Magazin

ID : -
Width : - mm
Weight: - kg
Place : -
Life : -

Figure 5. Display of APC machine control: working tool magazine.

productivity and flexibility by limiting disturbances. Handling material from one machining centre to the next is no easy job. A lot of system optimization approaches including layout, etc., are known today (Irani 1999). First a decomposition of these processes is recommended: identification of work piece, specification of work piece location, choice of gripper, fixing of grip points, gripping, etc. Next, the developer has to decide which task has to be performed by humans and which by machines. Two tasks were identified that need a very high degree of flexibility, which the human 'flexible controller' can do best without any significant cognitive effort: (1) choice of gripper; and (2) fixing of grip points. Consequently, operator's task spectrum was enriched in Active-UI by those tasks (Reuth 2001b). Depending on the manufacturing order the operator has to select an appropriate gripper (also available in a listing including pictorial representations). The process of fixing the grip points is shown in figure 6. During display design developers especially took rules 1–3 into account, as this task is merely of a skill-based nature. A cone is used as the essential design element to support user-interaction as it shows the operator the maximum range within which each gripper is able to suck the work piece (each grip finger is able to adapt 3° permitted deflection). This gripper has three grip fingers that have been developed for pneumatic transport of metal sheets. During the positioning of the grip finger the user is supported through colour coding. If the final finger positions are well suited, the cone is highlighted in green. If the grip finger is outside the cone, the cone is shown in signal-red. The top hats under the grip fingers support spatial orientation in the virtual world.

9. Reflection of implementation

It was considered whether the different measures for user interface design have had an effect on usability and human error compensation. Table 9 shows an overview of applied guidelines for each case of implementation separately.

In table 9, except for case 1, investigations of usability took place. According to case 2, in terms of Active-UI, a sophisticated evaluation was carried out by Schlick *et al.* (2000). Thereby, four usability criteria of the ISO 9241/10 (1996) standard were investigated empirically: (1) suitability for the task; (2) self-descriptiveness; (3) controllability; and (4) conformity with user expectations. The test subjects were experienced workers in the field of 3-D laser welding and had no knowledge about Active-UI. A total of nine experts in 3-D laser welding participated in a 100-min study. The experimenter gave the user standardized interaction tasks and the interaction behaviour was observed and recorded on videotape. In addition, the input activities like the trajectory in the model world as well as all state transitions of user interface objects were written into a logfile. Results for suitability of the task show that all users were able to process a welding order—from sensor set-up to quality control—completely and correctly with Active-UI. Self-descriptiveness of objects increased to 79%. Controllability showed that a mean of 93% of the sub-tasks were finished correctly by the users. Finally, results for conformity with user expectations show that Active-UI's metaphoric approach is sufficiently able to develop and support users' mental model. According to these results, the concept of error-compensating design is supported by mental compatibility and appropriate user interaction feedback on all SRK levels. Owing to this, the users were able to update their mental model of process states at any time and to undo their last interaction step if affordable.

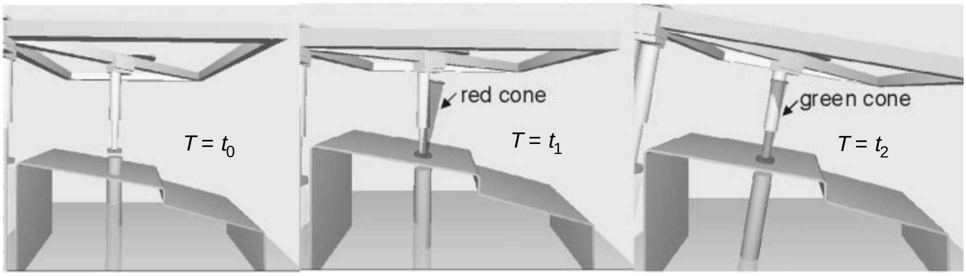


Figure 6. Sequence of grip finger positioning.

Table 9. Overview of applied guidelines in user interface design.

	Guidelines									
	1	2	3	4	5	6	7	8	9	10
Case 1		●	●			●	●	●	●	
Case 2	●	●	●	●	●	●	●	●	●	●
Case 3		●	●				●	●	●	
Case 4	●	●	●				●		●	

A recent unpublished investigation of the APC machine control UI compared with a commercial machine control UI was carried out testing 10 experienced industrial workers. A balanced experimental design was used where each subject had to use both machine control UIs. After an entire briefing of functionality and description of relevant UI objects the subjects were requested to perform the following tasks consecutively without any breaks: (1) loading of NC program; (2) check of machine initial point; (3) loading tool magazine (see Case 3); and (4) monitoring of machine processing. None of the subjects showed any difficulties in performing the tasks. Subsequently each subject had to rate different aspects of error-tolerance on a 5-stage ordinal scale. According to an undo-functionality, data input control, system warnings and comprehensibility of failure messages showed no significant differences (*t*-test, $\alpha = 5\%$). Support in error recovery shows significant differences in favour of APC ($t = 0.019$) stressing the error-compensating design. In general, the use of a touch-screen in APC machine control UI was rated as well adapted to an operator's needs at the shop floor. Indeed, the strongly nested navigation structure could be improved in APC.

Results of evaluation presented in Case 2 were to some extent also valid for Case 4 as the tasks 'selection of gripper' and 'positioning of grip-fingers' are part of Active-UI and the same design principles have been applied. Using a pluralistic cognitive walkthrough technique results of empirical evaluation (Reuth *et al.* 2001b) show that the suitability for the task is well adapted as users positioning tolerances are graphically visible.

10. Conclusions

Human errors play a dominant role in overall system performance in FMS. According to the domain of application the central leitmotif in developing APCs is expressed by trying to achieve nearly trouble-free production. Having the paradigm of supervisory control in mind most of these human errors are related to or propagated by HCI. Thus, the operator's work environment in terms of appropriate UI design is of central interest. However, the software life cycle is neither a well-ordered progression from problem formulation to solution implementation and its later utilization, nor is it a conscious, rationally planned process. In fact, it is an iterative development process using different evaluation techniques and 'lessons learned' for an improved system design. With respect to the different case studies results show that the relation between error analysis and provision of guidelines for an ecological interface design seems to be a promising way for a successful implementation, as cognitive task analysis and error analysis are strongly related. The provision of a methodological analysis approach of human errors based on HEDOMS and GEMS supports the UI designer to understand the phenomenon of human error in terms of HCI. The ability to prioritize these human errors according to safety and production consequences helps the UI designer where to focus in the development process. Dealing with such complex UIs it is of great concern to understand and to support human information processing by appropriate computer aid at all SRK levels. This can be ensured by Vicente's and Rasmussen's (1987) guidelines for an ecological UI design (see case studies), as they support all SRK levels and even more incorporate the avoidance of different types of human errors.

To sum up, the recommended approach for an error-compensating UI design has had positive effects on user interface design in terms of mental compatibility, improved usability and error-compensation.

Acknowledgement

The research was funded by the German Research Foundation according to the collaborative research center no. 368, *Autonomous Production Cells*.

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