# Development of a Design Guide for Telepresence – Teleactions Systems

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## Summary

This contribution discusses the development of a human factors guide for Telepresence – Teleaction Systems, which could provide a source of reference for engineers. Empirical results of user, task and technology analysis, which constitute elements in this tool, are presented. First, four different groups of operators (fast reactors, exact coordinators, anticipators, immersive) are distinguished and described by linear functions. Second, three different scenarios (microassembly, minimally invasive therapy, virtual product development) are compared on the level of sensorimotor elements and dependencies are expressed by linear functions, too. These terms are crucial as they lead to functional relationships and enable to generalize from specific evaluation results. Third, an example of such an evaluation procedure is presented by a microassembly scenario. Here, besides other things, it could be shown that haptic feedback enhanced with a cross-modal display evokes the highest sense of presence. According the same pattern a series of other scenarios are examined at the moment. Finally, reverting on the discovered mathematical dependencies these separate results will be linked and integrated in a design guide.

# 1 Introduction

The presented work is funded as part of the SFB 453 Collaborative Research Center ‘High-Fidelity Telepresence and Teleaction’ of the Deutsche Forschungsgesellschaft. This is a group of engineers and psychologists designing and evaluating Telepresence – Teleaction Systems with main focus on haptic interfaces. Thereby a wide variety of applications are considered ranging from microassembly, minimally invasive therapy to virtual product development[1].

From a human factors point of view the major challenge is to identify functional relationships among scenarios and to avoid categorical approaches. Only this way results are attained that can be generalized from a specific experimental setting to further evaluation efforts. Therefore the development process follows a three-step procedure: First, a representative sample of operators is assessed in terms of abilities and skills which are assumed to have impact on the design of Telepresence – Teleaction Systems. Since this user analysis is computer-aided it can easily be administered by end users and new operators are screened quickly. Second, in order to make different scenarios comparable a descriptive analysis of task is carried out. As this procedure is standardized, too, new scenarios can easily be compared with the available data basis and end users are informed about the quality of prognosis. Third, this analysis of tasks and assessment of operators serves as a source of hypotheses that are scrutinized in experimental evaluations. In a next step single evaluation results are related to each other, raised on a more general level and integrated in a guide. Finally engineers, who provide a profile of their operators and the considered application, will be able to choose (about four) variables out of a list of all examined factors and following questions will be answered: How good is the prediction quality of the design guide in this special case? Which characteristics do operators show and how do these influence the design of interface? Which combination of the chosen stimuli will be best (in terms of presence or performance)? Which of the selected variables constitutes a key factor and is most relevant to achieve sustained changes? Figure 1 gives a graphic presentation of this process:

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[1] Though, strictly speaking, the term ‘Telepresence – Teleaction’ does not cover virtual simulations, these are regarded here, too.

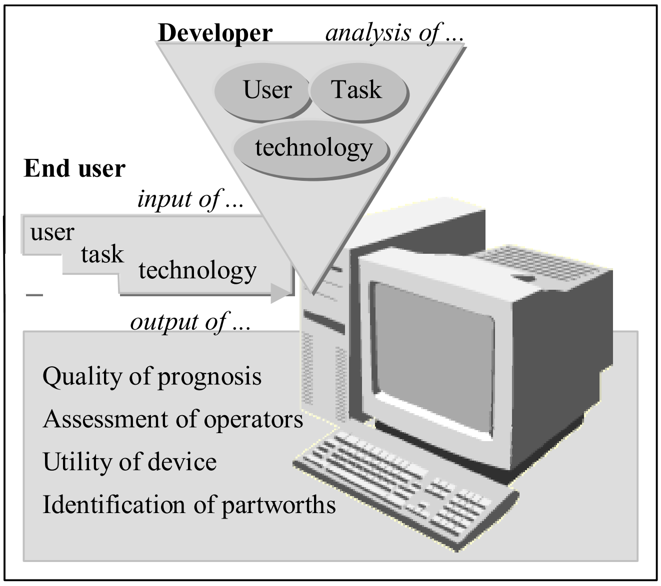


*Figure 1: Development of a design guide for Telepresence – Teleaction Systems*

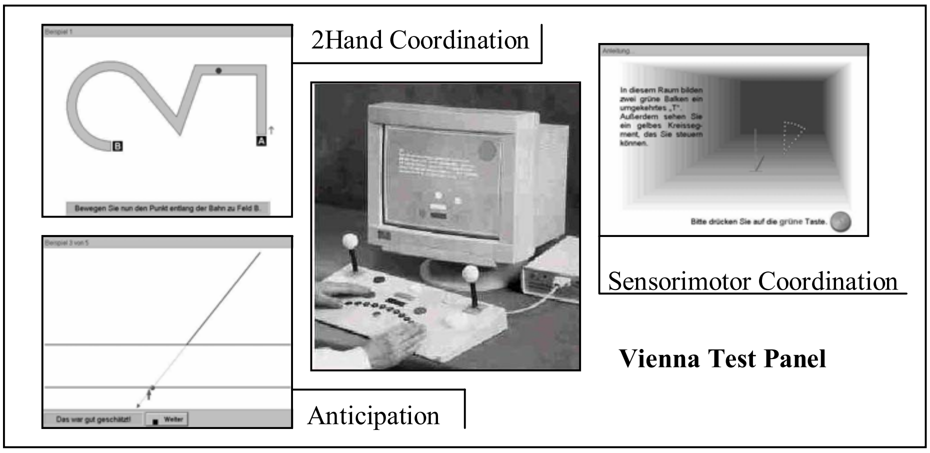
## 2 User Analysis

In order to guarantee the success of an interface it is necessary to tailor it to the need of operators and define distinctive user groups. For identifying user groups we do not separate operators on a macro-level (e.g. age, profession), but concentrate on an operator's tendency of immersion, his or her preference for a sensory modality and his or her sensorimotor skills.

In this context **immersion** is understood as a cognitive parameter of perception and not as a description of quality of interface (see Slater, Linalis, Usoh & Kooper, 1996; Slater & Wilbur, 1997; Schubert, Friedmann & Regenbrecht, 1999, Kalawsky, 2000): "Immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences" (Witmer & Singer, 1998). For measuring this individual experience a questionnaire was applied which was developed by Scheuchenpflug (2001). This instrument expresses immersion as a sum of two subscales named 'emotional involvement' and 'degree of involvement'.

The operator's **sensory preference** was taken into account as a second parameter of perception. This parameter is clearly visible in different learning styles: Whereas some people profit more by visual training material, others are supported best by acoustic presentation. Correspondingly people may feel more present whether information are displayed visually, acoustically or haptically. Here the Barsch Learning Style Inventory (Barsch, 1996) is applied, which distinguishes between visual, auditory, tactile and kinaesthetic learning style.

Whereas the traits mentioned above are assessed by conventional paper-pencil tests, **sensorimotor skills** can, however, hardly be analyzed conventionally. That's why the Vienna Test System was employed, which enables computer-aided psychological diagnosis with a specific test panel for the analysis of technical-motor ability. Three components make up the core of the testing: anticipation of time and movements of objects, sensorimotor coordination between eye and hand as well as between the left and the right hand. A battery of three tests are administered which follow an instruction and a practice phase as well as an actual test phase. The first test is called 'Time-Movement Anticipation' and assesses the extent to which a person can "project into" a motion and correctly estimate the movements of objects in space (Neuwirth, 2000): A green, slowly-moving dot appears on screen. After a certain time it disappears and two red lines appear. One is located at the place at where the dot has just disappeared. The other line is the target line, with which the time of the appearance of the dot is to be specified. To this end the subject presses a button at that moment at which s/he believes the dot should have reached the second line. An arrow then points to the spot at where it should have appeared. The difficulty of the items varies as follows: At first simple line movements appear; then curved paths follow. These are replaced by sine curves which run constant at first then amplitude-modulated, frequency-modulated and finally frequency-amplitude modulated. The second test is called 'Sensory-Motor Coordination' and covers mainly a subject's reaction to unpredictable changes in distance and size (Prieler, 2002). Therefore, a target (green bar-cross) and a control element (yellow segment) are displayed within a perspective space. The segment is standing on its tip and moves in three directions: There is a rotatory, a horizontal as well as a depth movement. Though these movements are the same for all subjects, they are unpredictable. The task is to balance out the segment with two joysticks, so that it is positioned exactly on the beam-cross. Finally, the third test is named 'Two-Hand Coordination' and analyzes speed, accuracy and coordination performance in fine, narrow movements (Puhr, 2001). The subjects use two joysticks to move a cursor along a track shown on a screen. Using one element, the cursor can be moved horizontally, using the other element it can be moved vertically. The track should be carried out from start to finish as quickly as possible; whenever the cursor goes off the track, it is counted as an error. This track consists of three sections which make different demands on the coordination of the left and the right hand (circular arc, V-shape, inverted L). In order to get an idea of the tests, Figure 2 provides snapshots. Existing reliabilities (internal consistency) show favorable results for all the three tests. Besides, validity studies are available in performance and suitable diagnostics for construction drivers, engine drivers and crane operators as well as personnel for steering and supervision.



Bewegen Sie nun den Punkt entlang der Bahn zu Feld B.

In diesem Raum bilden zwei grüne Balken ein umgekehrtes „T“. Außerdem sehen Sie ein gelbes Kreissegment, das Sie steuern können.

Bitte drücken Sie auf die grüne Taste.

Das war gut geschätzt!

*Figure 2: Vienna Test Panel with a snapshot of the applied tests*

## 2.1 Setting and Design

The user analysis mentioned above took thirty minutes per subject. In a total, eighty participants were tested, who were all asked to take part in a later evaluation of the interface for a second time. The sample was chosen in consideration of the Telepresence – Teleaction scenarios under evaluation. Surgeons of a local hospital, who are all experienced in minimally invasive therapy and used to high-tech equipment, were contacted as potential users of the medical interface. With regard to virtual product development engineers of a car manufacturer, who are trained in CAD tools, could be gained as participants. Finally, concerning the microassembly application, mechanics were recruited. Since it is of interest for the first two scenarios to compare novices and experts, medicine and engineering students were addressed, too.

In order to identify groups of homogenous users a **hierarchical cluster analysis** was realized (Backhaus, 2000). To meet the assumptions of this procedure only uncorrelated and z-standardized variables were considered. As a measure of proximity between cases, squared euclidic distances were calculated. Subsequently, cases were merged to groups by Ward Algorithm. Whereas a cluster analysis is able to identify user groups, a

**discriminant analysis** can serve as a useful second step which provides two advantages at least. On the one hand it is possible to verify discovered clusters and point out variables that are especially essential for separating groups. On the other hand this procedure generates a linear function (Fisher's function of classification) with which it is possible to group new cases. This prediction is particularly important with regard to the later use of the design guide: Engineers (as end users of the tool) can administer the user analysis mentioned above. Since item presentation, as well as scoring, will be computer-aided this psychometric test battery is easy to handle. Subsequently, raw scores are gathered and entered in the corresponding Fisher's function. On this basis 'new' operators can be classed with the appropriate user group and design recommendations can be drawn.

## 2.2 Results and Outlook

The cluster analysis reveals four different groups of operators. This fact is indicated by the so-called 'ellbow criteria' (a sudden jump in the distance coefficient). The first cluster may be labelled **'Fast Reactors'** as group members are particularly distinguished by spontaneous reaction on unpredictable coordination demands. This is expressed in high scores in 'Sensory-Motor Coordination' and matches their subjective self-assessment: These people call themselves haptically oriented as well as immersive. The second group can be summarized as **'Exact Coordinators'**. They are able to perform fine-motory movements in narrow spaces as mirrored in the 'Two-Hand Coordination'. Compared to the first group, these operators are less accurate in speed estimate; therefore, reaction to dynamic changes is a greater challenge for them. Again, subjective rating scores correspond to the objective index. Haptic sensation is less dominant and people feel hardly immersive. The third group can be termed **'Anticipators'**. This cluster is especially suitable to estimate distances and even highly complex movements of objects. In contrast to the groups mentioned above it is more difficult for them to transform this cognitive anticipation to corresponding motor reactions. It is not surprising that these users rely less on haptic sensation and are only little immersive. The fourth group shows low fine-motory skills but is quite easily drawn in incidents and may be called the **'Immersive'**. However, none of the groups is dominated by left/right-handers or a certain profession. Moreover, no significant distribution of age or gender could be observed. Figure 3 gives a graphic representation of these clusters.

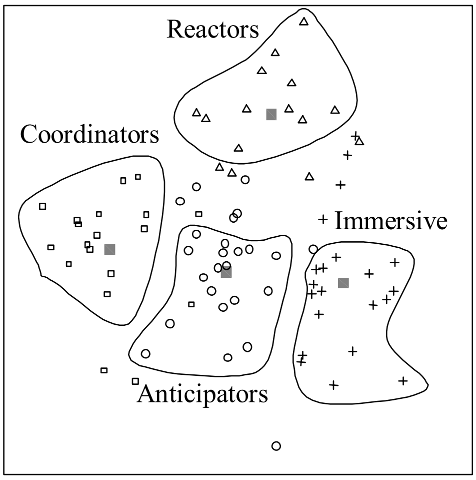


*Figure 3: Groups of users as revealed by the cluster- and discriminant analysis*

The cluster analysis serves as a basis for the developer as well as for the end user: For the development process hypotheses are postulated for each group and scrutinized in the following technological analysis (e.g. "Operators who describe themselves as less immersive require a particularly high quality of display technology for compensation"). In order to be relevant for the end user, a discriminant analysis is connected to the cluster analysis. This procedure generates four linear functions of classification, as displayed in Table 1, and new cases are grouped to that cluster for which the highest value is obtained. Since cross-validation (each case is classified by functions that are derived from all others except cases the observed case) yields that 90% of the sample are classified correctly, the functions can be regarded as a good predictor for new data.

*Fast Reactors*

$$F_1 = 17.4 \cdot x_1 - 13.5 \cdot x_2 + 0.6 \cdot x_3 + 0.5 \cdot x_4 + 0.7 \cdot x_5 + 1.2 \cdot x_6 + 2.3 \cdot x_7 - 119.4$$

*Exact Coordinators*

$$F_2 = 18.0 \cdot x_1 - 13.2 \cdot x_2 + 0.5 \cdot x_3 + 0.5 \cdot x_4 + 0.8 \cdot x_5 + 1.7 \cdot x_6 + 1.8 \cdot x_7 - 92.4$$

*Anticipators*

$$F_3 = 14.0 \cdot x_1 - 4.4 \cdot x_2 + 0.4 \cdot x_3 + 0.4 \cdot x_4 + 0.5 \cdot x_5 + 2.3 \cdot x_6 + 1.1 \cdot x_7 - 82.8$$

*Immersive*

$$F_4 = 22.1 \cdot x_1 - 17.8 \cdot x_2 + 0.7 \cdot x_3 + 0.7 \cdot x_4 + 0.9 \cdot x_5 + 2.1 \cdot x_6 + 2.1 \cdot x_7 - 144.2$$

| | | | |
|---|---|---|---|
| $X_1$ | 2Hand coordination | $X_5$ | Vertical sensorimotor coordination |
| $X_2$ | Anticipation of time | $X_6$ | Haptic sensory preference |
| $X_3$ | Anticipation of direction | $X_7$ | Immersion |
| $X_4$ | Horizontal sensorimotor coordination | | |

*Table 1: Fisher's function of classification.*

*New cases are merged to the cluster for which the highest result is received.*

# 3 Task analysis

To avoid categorical approaches and consider functional relationships among these elements, a cognitive analysis of the task is worked out. In order to be relevant for different applications (minimally invasive therapy, microassembly, virtual product development), issues are limited to basic operations and concentrate either on motor-dominant manipulations or sensory-dominant explorations:

Among other things the **manipulation** choreography, the way objects are grasped, is explored (Burdea, 1996; 1999). Grasping geometry has been classified by two categories, namely power and precision (Cutkosky & Howe, 1990). Since the whole hand and palm are used, power grasps have high stability and force. At the same time they lack dexterity because fingers are locked on the grasped objects. Conversely, precision grasps exert less force but have higher dexterity since only the fingertips are used. Typical power and precision grasping configurations are illustrated in Figure 4 (left).

Besides, people use a set of **exploration** procedures to gather information about objects. As displayed in Figure 4 (right), Lederman and Klatzky (1987; 1993) distinguish between eight fundamental gestures, which are applied to experience texture, hardness, temperature, weight, volume, shape, specific function or part motion of objects. Whereas in a cancer screening, for instance, physicians seek to get information about surface and smoothness of tissue and therefore perform lateral motions or put pressure on the body, mechanical joining processes are especially supported by information on movability and functionality of single parts.

Within a workshop, these haptic elements were presented to and discussed with engineers. As experts for the devices, they were asked to rate the scenarios with regard to these categories. Their retrieval process was supported by presentation of visual cues, because it is not easy to call abstract haptic issues to mind. In order to derive functions of classification, a discriminant analysis was calculated afterwards on the basis of these judgements.

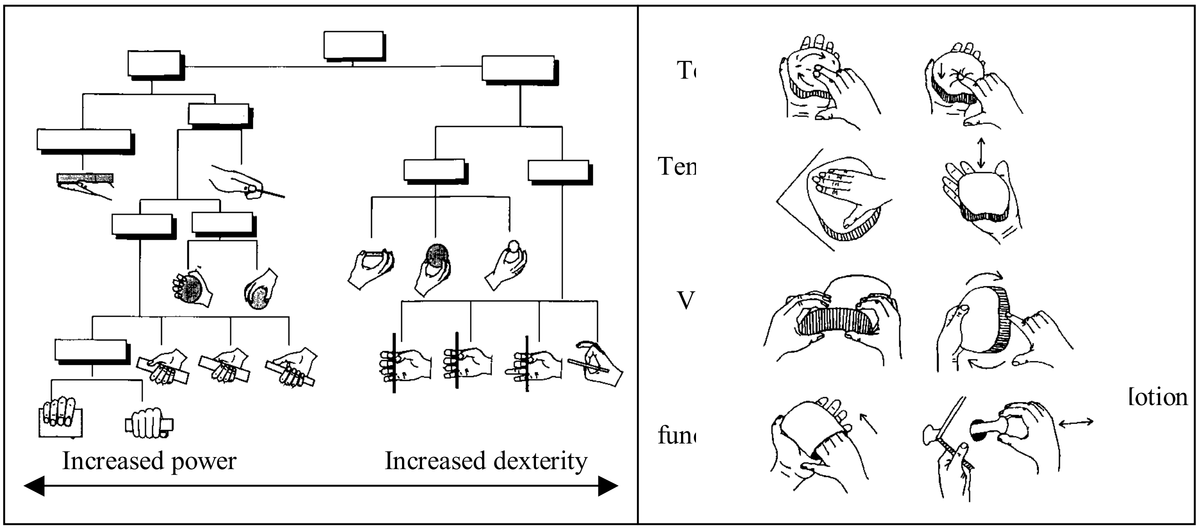


*Figure 4:*
*Left: Manipulation procedures – Source: Burdea 1996 (p.23)*
*Right: Exploration procedures – Source: Lederman & Klatzky, 1987 (p. 344)*

### 3.1 Results and Outlook

The discriminant analysis led on to two dimensions, along which the scenarios can be distinguished. The abscissa explains 91,8% of variance and therefore constitutes the essential criterion for separation: Lower values on this axis describe scenarios that derive most benefit from **geometrical information** of objects (volume, functionality); there are higher values when a rather precise grasp is executed and **surface information** of objects (texture, consistency) is required. As Figure 5 illustrates the microassembly and the virtual scenario are described as being similar. This is due to the fact that the examined virtual simulation refers to an assembly task, too. The remaining variance of 8,2% depends on the favored objective and may be summarized as a question of **speed** or **accuracy**: For the success of an industrial microassembly application, for example, it is relevant to enable fast as well as high-quality production. Since in the field of virtual product development no harm can be done to material, it is only important to provide an interface which is fast and easy to handle. However, it is obvious that in the medical application accuracy is appreciated.

Similar to user analysis, cases are cross-validated and Fisher's functions are derived here, too. To sum up, the main contribution of task analysis is to make various scenarios comparable in relevant issues. This is important both for the developer and the end user: The end user, on the one hand, is informed about the quality of recommendation which depends on the correspondence of the entered scenario to the data. The developer, on the other hand, can rely on the functional relationship between scenarios and derive systematic hypotheses (e.g. “The more precise the required grasp, the more important it is that the applied control device resembles the conventionally used tool.”)

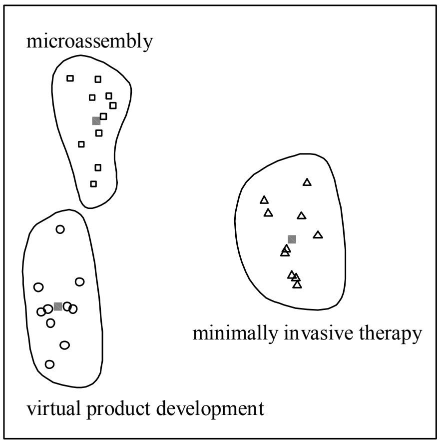


*Figure 5: Map of tasks as revealed by discriminant analysis*

## 4 Technology Analysis

Whereas user and task analysis represent the framework of the guide, the evaluation of technology constitutes the core. In order to reveal relevant independent variables, engineers are interviewed again and experimental set-ups are defined (as demonstrated below on the example of a microassembly scenario). Whereas these factors vary from scenario to scenario, the dependent variables remain the same. Two evaluation criteria are of interest: One of the main goals in the field of Telepresence – Teleaction Systems is to induce a feeling of actually “being there” in users, a sensation which is commonly called presence (Draper et al., 1998). Concerning industrial applicability, it is also necessary to consider individual performance.

We decided to capture **presence** by a questionnaire technique. This procedure is not only easy to administer, but also avoids disruption of performance. The instrument we applied was developed by Scheuchenpflug (2001) in order to compare the quality of virtual driving simulators. Items were mostly derived from published questionnaires (Kim & Biocca, 1997; Regenbrecht et al., 1998; Witmer & Singer, 1998) and were translated into German if necessary. After the deletion of uninformative items, the reliability (Cronbach’s alpha) was 0.85 for the presence scale. Factor analysis revealed that three factors contributed to the impression of presence: The first factor taps into the difference between physical and virtual localization and can be called ‘spatial presence’ (Schubert et al., 2001). The second factor refers to the interaction between the control device and the display and might be termed ‘quality of interface’. The third factor is composed of items addressing ‘emotional involvement’. This factor structure confirms earlier findings based on different methods: cluster analysis (Witmer & Singer, 1998) and direct oblivion rotation (Schubert et al., 2001).

Individual **performance** can be measured by operational definitions of either speed (time-to-complete) or accuracy (maximum contact forces, number of collisions). The exact focus, however, is mostly determined by the single scenario.

## 4.1 Factors and Method

The proceeding is demonstrated by an experimental set-up of a microassembly scenario. In this example a presence questionnaire is administered and time-to-complete is measured. Besides, these four independent variables are of interest:

One of the main problems during the assembly of micro-components is the correct estimation of applied contact forces. A certain minimum pressure has to be applied in order to establish stable contact, while a certain maximum force must not be exceeded to avoid component destruction. Thus, it is relevant for the design of the interface to know whether a **haptic display** would support operators or not.

A well-validated principle in the human factors of design concerns the advantage of redundancy in presenting information in a variety of forms (Wickens & Backer 1995; Wickens & Hollands, 2000). A **cross-modal display**, such as the application of a bar graph, translates force information into a visual arrangement. On the one hand this type of display keeps the user feedback in the information domain; on the other hand it is linked to an extra cognitive burden of transforming visual information into force domain relative to hand (Hannaford & Venema, 1995). Consequently, the question arises whether a bar graph would be able to enhance or substitute a haptic display or not.

Though the importance of redundancy remains unquestioned, its design is an important factor to be examined. For instance it would also be conceivable to use an **acoustic display** instead of a cross-modal display. This acoustic contact cue would provide less haptic information, but it would be much more intuitive. So its effect is also worth to be examined.

Besides choosing the appropriate form of feedback system, engineers are also faced with asynchrony problems between modalities. At the worst case, **latency** between haptic and acoustic information, for instance, might take up to 500ms. It would be interesting to observe whether such delays are top-down corrected to a consistent perceptual evidence or not (England, 1995; Wenzel, 1999).

Although it is possible to examine these factors by an analysis of variance, this procedure would limit evaluation in the effect of single variables. Since factors are never experienced separately but add up to one perception, it would be much more sensible to focus on the whole system. This is possible by a **conjoint analysis**, which assumes that single variables add up to the total utility of the system (Backhaus, 2000). That's why the utility of the whole system is considered (e.g. as indicated by time-to-complete or sense of presence). This measurement is decomposed and partworths of single features as well as the averaged importance of variables are determined, so that finally two questions may be answered. Firstly, which combination of stimuli achieves the highest performance or sense of presence? Secondly, how big is the percentage contribution of a single variable to the total utility?

It is obvious that it would not be feasible to realize all possible factor combinations. Even the four-factor design described above would require 36 (= 2 x 2 x 2 x 2) experimental set-ups, as each factor has two possible features. Thus, results have to be derived from a reduced design which constitutes an adequate representation of the complete design (see orthogonal arrays; Addelman, 1962). To sum up, it will be sufficient to realize eight (instead of 36) experimental set-ups in the microassembly example in order to identify the best combination of the four factors and to draw conclusions on the averaged importance of the single variables.

## 4.2 Setting and Design

Results are derived from a laboratory experiment for which sixty subjects (assembly operators, engineering students, mechanical engineers) were recruited. A pick-and-place task which contains a model for a more complex industrial application serves as an experimental scenario. In order to avoid unintentional disturbances that can be created by sensors or framework the operator end is isolated from the remaining system and is run as a simulation. As a haptic control device, a PHANToM is applied, which offers a force feedback of maximum 8.5 Newton.

The subjects have to grasp a simplified virtual gear wheel and attach it to a virtual gear shaft as illustrated in Figure 6. When the PHANToM cursor is in contact with the gear wheel it can be picked up with a button click on the PHANToM stylus button. Then, the subjects are able to move the grasped object in six degrees of freedom in order to place it as requested. Furthermore, a virtual fixture is offered which functions as a permeable anchor (and therefore does not provide feedback). This additional help increases depth perception and facilitates navigation in the three-dimensional virtual space.

*Figure 6: Experimental set-up*

As the subjects were to be ‘blind’ (i.e. uninformed about the setting), the instruction was reduced to a minimum. The experimenter only demonstrated the sequence that was experienced later as well as all relevant features: The operator learned how to move the device, how to grasp the object and how to profit from the virtual fixture. However, participants were not explicitly told whether they would experience a certain sensory feedback or not. Subsequent participants could run one test trial in which task performance was not timed. After having answered the last questions, the participants were asked to do the assembly task as fast as possible. Now the time from the first movement of the device until a certain defined target area was reached was measured. Finally, the presence questionnaire was answered.

### 4.3 Results and Outlook

For this microassembly scenario results of conjoint measurement are exemplified for the dependent variable presence across all subjects. Just the same it would be possible to point out results for performance or to present the outcome for a distinctive group of operators.

Here it is shown that the average operator feels most present when haptic feedback is provided and enhanced by a cross-modal bar-graph display. Interestingly an additional acoustic contact sound, especially a delayed one, is sensed as more disrupting than helpful. In contrast the least preferred stimuli is a display that lacks haptic and acoustic information and presents contact forces solely by a cross-modal bar graph. Thereupon it may be concluded that a cross-modal display is a valuable enhancing stimuli, but, however, is not accepted as substitution for haptic. Up to now this result is only true for microassembly scenarios. But as it is examined in other tasks (between interdependencies are exactly defined) more specific conclusions can be drawn soon.

Furthermore the averaged importance of factors is regarded: Here the most sudden improvement is achieved by adding haptic stimuli, followed by a bar graph. The contribution of a (delayed) acoustical contact sound is less important. Of course, vice versa the absence of these features contributes in the same way to a decline. Among other things it may be concluded for the design process: Engineers who work on this microassembly device are well-advised to focus especially on force feedback as it dominates the sensation of presence. In addition the effects of delays (up to 500ms) have less effects on the sensation of presence and are therefore less crucial. Again, in order to raise conclusions on a more general level the relevance of these and other factors will also be explored for further tasks and operators. Finally, this systematic proceeding will make it possible to link single results and integrate them in a design guide for Telepresence – Teleaction Systems.

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