Chapter 7

Conclusions and Future Work

This thesis is a careful investigation of distributed, collaborative interaction between geographically dispersed teams using projection based Virtual Environments.

In the beginning of this work the basics of Virtual Environments (VE) and Collaborative Virtual Environments (CVE) were described. These are different rear-projection based display systems like the CAVE and the Responsive Workbench. In addition, different devices for interacting with the Virtual Environment were presented such as the Cubic Mouse, pen-like six degree-of-freedom locator devices as well as haptic devices (Phantom). Different software toolkits were discussed with respect to distribution support. Avango as GMD's software framework was used to implement the applications developed in this work. The basic concepts of Avango were described briefly in chapter 1 and in more detail in the implementation chapter 5. Thereby Avango's field interface was described as well as the importance of field connections. Additionally it was explained how the distribution mechanism makes use of this field interface in order to handle the database duplication problem.

The related work relevant to this thesis was presented in chapter 2. This includes a detailed discussion of interaction techniques which are applicable in two-dimensional Graphical User Interfaces (GUIs) as well as in three-dimensional Virtual Environments (VEs). However, it was possible to show that a usage of two-dimensional interaction techniques in three-dimensional VEs is non-trivial. Most of the techniques have to be modified to be able to fulfill three-dimensional requirements. Hence, new techniques especially for Virtual and Collaborative Virtual Environments have been developed. A good reference frame for doing this represents body-relative interaction for rear-projection based Virtual Environments. In combination with other techniques such as speech recognition new and intuitive three-dimensional interaction techniques are designable. Additionally, a survey on selected Collaborative Virtual Environments was presented which were chosen due to their use of tele-immersion approaches. The objectives of the CVE applications were introduced and it was shown how interaction in these Collaborative Virtual Environments is designed.

From the basic chapters 1 and 2 as well as during the presentation of the different CVE approaches it became clear that the absence of a classifying framework for collaborative interaction is the most challenging problem when designing VEs and CVEs. Hence, chapter 3 presents the theoretical approach of this work with which designers and programmers are able to analyze user tasks and interaction cycles in VEs. The results of this analysis, describe a User+Need Space (UNS) which determines the appearance of the Collaborative Virtual Environment. Performing the mapping of the UNS to the CVE representation components is elaborated. These representation components are user representation, remote user representation, data model representation and functionality, environment representation, virtual input device representation and virtual tool representation. In order to find the best interaction the low-level makeup of interaction is analysed. Therefore interaction tasks were narrowed down and interaction templates were found. The developed *Awareness-Action-Feedback (AAF)* loops are such interaction templates. These AAF loops provide the possibility to understand and analyze very tiny steps in interactions. With their help it was possible to form complex interactions through the combination of these loops. Together with the analysis of Awareness-Action-Feedback loops for autonomous and collaborative interaction cycles the desired Application+Interaction Space was determined.

An example application was developed and described in detail in chapter 4 using the theoretical approach. A User+Need Space was determined exemplarily. The interface and application specific information was provided according to a task involving two users and using a Responsive Workbench-Responsive Workbench setup as well as a Responsive Workbench-CAVE setup. Starting with a detailed User Task Description all necessary representation components, metaphors, operations and interaction techniques are determined.
With the description of a currently developed CVE combining a Responsive Workbench, a CAVE and a Cylindrical Display is was possible to exemplify the application design process of very complex CVE. The User Task Description for this CVE describes an adventure game based multi-user experience for practising team work.

CVE implementation details were introduced with respect to the used hardware and the software configuration in chapter 5. The hardware configuration was presented for a distributed setup using the two Responsive Workbenches, and for the distributed setup using a Responsive Workbench and CAVE. These two configurations include input devices for interaction, computers for rendering and distribution, and computers for video and audio streaming. Additionally it includes equipment such as shutter glasses, infra-red emitters, cameras as well as microphones and headphones.
In addition to the detailed description of Avango the video conferencing software for Immersive Telepresence was presented. This was done with respect to the mono and stereo video conferencing capabilities. A solution for sending synchronized stereo video frames was introduced as well as a solution for the integration and rendering of the synchronized stereo images in the CVE.

Evaluation Conclusions

The evaluation of the described and implemented CVE application in chapter 6 was producing many different results assessing usability aspects of CVEs and collaborative awareness in these environments. The theoretical evaluation approach for Collaborative Virtual Environments was derived from the developed Human-Computer-Human interaction model presented in chapter 3. With the help of this evaluation framework 60 non-VE-expert evaluators assessed the CVE.
For doing so, alternating cycles of expert heuristic, formative, and summative evaluation were applied. For performing an advanced evaluation, specific questionnaires and evaluation items were designed. The results of the evaluation were analysed separately according to the Expert Heuristic Analysis, the First Level Analysis, the Group Analysis and the especially developed Variation Group Analysis. The results of these analyses were used for the formulation of CVE design guidelines supporting team work. The usability findings and recommendations of the expert evaluators are concerned with the following items:

- positioning of the toolbar, which groups together generic operations
- handling of the ring menu grouping content specific operations
- tool representations on menus
- three button input device and stylus vs. pinch gloves
- ego-centric vs. exo-centric viewpoint manipulation
- graphical representation of data sets

- video frame rate

From the First Level Analysis, the Group Analysis and the Variation Group Analysis it was possible to present results that concern immersive telepresence, representation of input devices and disturbance factors of collaborative awareness.

First Level Analysis

The results found during the First Level Analysis are:

Immersive Telepresence (First Level Analysis)

- In an educational scenario immersive telepresence supports the work flow. In this situation network drop outs do not have a negative impact on the perception of co-presence as long as the average frame rate does not go below 12fps.

- In a collaboration scenario using immersive telepresence the position of the remote partner representation should be chosen in a way that both partners seem to have same virtual size in the CVE independent from their physical size in real world. This is particularly important when partners are given equal rights for manipulating the data as it was the case in the co-work sessions.

- When using a Responsive Workbench the perception of co-presence can be increased with a remote partner's video texture representation together with a real background. Because of the depth perception the user has the impression that the remote partner stands closer to the table. This effect is not obtainable if the partner's outline is cut out using chroma keying techniques.

Input Device Representations (First Level Analysis)

- Appropriate representations of the remote user's tools and input devices support collaboration more than body and hand gestures.

Disturbance Factors (First Level Analysis)

- Cabling of input devices, trackers and stereo glasses are perceived as annoying. Careful handling of loose wires is recommended.

Group Analysis

For handling the problem of the spread answer patterns group analysis was used in the third part of the analysis. Results obtained by this analysis method concerning immersive telepresence, representation of input devices and disturbance factors are:

Immersive Telepresence (Group Analysis)

- When integrating immersive telepresence into a CVE, audio and video streams do not necessarily need to be synchronized unless the delay is bigger than 10 frames. Even the resolution plays a tangential role, since participants spent most of the time looking and working on the virtual data.

- The experiments show that the remote partner representation is crucial in situations where problems need to be resolved. The use of the video connection enhances the collaboration at a psychological level but its quality can be traded off against other representation components.

Input Device Representations (Group Analysis)

- Appropriate tool and input device representations of the remote partner are adequate means for supporting the perception of co-presence which is the basic requirement for collaboration. With the help of these representations the influence of video is reduced to support collaboration only psychologically.

Disturbance Factors (Group Analysis)

- High system responsiveness is perceived as having very positive impact on collaboration. Even downsizing the application in order to decrease the CPU load is recommendable. A good system responsiveness is guaranteed if all inputs and outputs are processed and rendered within less than 50ms.

- Although the work with input devices is assessed to have negative influence, this perception seems to be very subjective. However, it is essential to facilitate the usage of VE input devices.

- Using descriptive text in a Virtual Environment the developers should ensure that the alignment is realized with respect to the user's physical size. Readability should be provided from any point within the CVE interaction space. This is especially interesting when using a CAVE-like display system or a cylindrical projection. In this case descriptive text can be attached to the user's gaze, body or input devices.

Variation Group Analysis

Although it was possible to encounter and interpret trends in the answer behaviour the statistical certainties of the computed average values were very low. In order to overcome this problem special evaluation parameters were determined. These parameters were changing the initial evaluation conditions for different groups. The presumption was that when changing the initial evaluation conditions by the evaluation parameters special answer patterns were provoked. This was producing better results than simply evaluating more users under the same conditions. The results of this especially developed Variation Group Analysis are:

- With the variation group analysis it is confirmed that the absence of representation forms has a negative impact on usability. It is proved by the statistical results from the variation group analysis that a missing remote partner representation handicaps the CVE team more than missing remote tool and input device representations. The intensification of a collaborative work session without restrictions in representations shows impact on usability too.

- In conjunction with the evaluation results obtained by the former analyses it is possible to formulate a CVE rating scheme.

CVE rating scheme

The CVE rating scheme consists of a chain starting with the audio link to the remote partner, which is proved to be the most important for a Collaborative Virtual Environment. Without audio it is impossible to work adequately. The next component is the video representation of the remote partner. Although this representation form is important it is not essential for the completion of the collaborative task. The users are able to compensate for this missing feature with other adequate tools or forms of communication (i.e. remote tool representation and audio). The third item is the remote tool and input device representation. These representations support completing the collaborative task but they are also not essential.

It is proved from the results of the statistical and group analysis that compensation always performs at the expense of usability or the perception of co-presence and co-knowledge. Users who do not suffer any missing representation features perceive the collaboration in a CVE as most satisfying. If only one feature is missing the users have to compensate for it by other adequate tools and mechanisms. As a consequence, the users are unable to concentrate on the task. The compensating tools and mechanisms stress the user's senses in a way that these become overloaded. Therefore, the users perceive the usage of equipment, virtual tools and menus as disturbing and confusing. Users who feel supported are rather willing to accept components, which are weak in terms of usability.

Further Design Guidelines

Finally it is possible to formulate some further guidelines with the results obtained by the variation group analysis:

- CVE design and realization should consider the CVE rating scheme.
- An audio link to the remote partner(s)/team needs to be more reliable than a video link. Synchronization of audio and video streams is not necessary as long as the delay is not bigger than ten frames.
- Appropriate remote tool and input device representations are supportive but with minor importance relative to the video link. If appropriate remote tool and input device representations are difficult to realize ensure that equivalent, compensating tools and mechanisms are offered. Action feedback is an appropriate solution for overcoming this representation drawback.
- Expert heuristic, formative and summative evaluations of the stand-alone Virtual Environment might not be able to identify weaknesses concerning the usability design for a Collaborative Virtual Environment. The alignment of virtual tools and menus as well as the usability of input and output device combinations and other equipment should be designed and implemented with respect to CVE evaluation results.
- Work tools and mechanisms should be designed for disburdening the users senses. High cognitive load, uncomfortable, non-intuitive usability and user fatigue have negative impact on the perception of co-presence and co-knowledge and thus collaboration.

Future Research

Beside interesting results concerning usability and collaborative awareness in CVEs the thesis offers a great amount of possibilities for further interesting and challenging investigations. The ideas for these further investigations concern the following most important items:

- **Framework:**
The structure of the taxonomy in chapter 3 is such that additional components and operations and metaphors can be easily incorporated. Refinements of the taxonomy allow for performing better design analyses and for obtaining more subtle results concerning usability evaluations.

- **Persistence:**
Persistence was not the focus of the thesis. However, it is the basis for long term collaborative work. Persistence here denotes the ability to save and maintain the state of the environment. For the realization of CVEs able to support distance education persistence should be considered. Thus its influence on usability and collaborative awareness should be analysed.

- **Disturbance Factors:**
It is necessary to investigate further evaluation parameters in order to screen a wider range of disturbance factors that might affect collaborative interaction in CVEs. The more disturbance factors are encountered the more valuable are the evaluation results.

- **Evaluators:**
Although the Variation Group Analysis is able to reduce the problem of high uncertainty values of the evaluator's answer behaviour, a higher number of experimental subjects should be evaluating the CVE applications. The higher the number of evaluators the smaller the standard deviation and the more certain the evaluation results.

- **Questionnaires:**
As it was possible to see from the variation group analysis it is necessary to design the questionnaires with respect to the type of analysis to be performed. Future work should try to design refined questionnaires for obtaining further results.

- **Interaction Techniques:**
This work was not analysing the usability of interaction techniques in particular due to the strong dependency of the task and application. Evaluation of interaction techniques and metaphors, however, needs to be performed for assessing usability problems of these environments.

- **Task Complexity:**
The implementation of more complex tasks should be considered. This allows for analysing the influence of the task's complexity on the user's behaviour working in the CVE. From the results obtained so far, it will

definitely have an impact on the perception of co-presence and the usability of input devices and tools.

- **Peripheral Influences:**
  For performing advanced usability studies of CVEs peripheral influences such as user preferences should be analyzed. These could consider the influence of highlighting colors, situation dependency, different representations of the remote partner, and positioning of the remote partner.

- **Multiple Sites:**
  The focus of this thesis was on teams working at two different sites. Most probably concepts for team work including more than only two sites will differ. To support multiple sites becomes extremely interesting when investigating the possibilities of CVEs for advanced remote education and game parks. The basis for investigating this special multi-site interaction problem is developed combining the Responsive Workbench, the CAVE and the Cylindrical Display for the adventure game based multi-user experience described in chapter 4.

The list above is a set of suggestions future investigations could go. Nevertheless, with the help of the methodology and tools developed and implemented in this thesis, the basis was created for investigating eminently interesting and diverse problems which are related to the design and development of Collaborative Virtual Environments.
Besides specific results, I hope it was possible to show that Collaborative Virtual Environments represent intriguingly interesting and modern working environments. Their further development as well as their application is extremely challenging and important for our modern society.