Construction of a Three-Sided Immersive Telecollaboration System

Abstract

In this article the setup and working principle of a new telecollaboration system "blue-c" is described. This system is an attempt to meet the rising expectations from industry of an IT-supported telecollaboration system. One basic requirement is that a three-dimensional representation of objects be possible together with three-dimensional representations of the remote users. Since gesture and mimicry represent an important information channel during a discussion, a realistic 3D video representation is used instead of simple animated avatars.

A simultaneous projection and image acquisition of the user in a telecollaboration system is necessary to allow simultaneous work of all team members. Thus, in the introduced system, problems had to be overcome such as providing, simultaneously, illumination for the image acquisition by the cameras and darkness for a bright projection to be seen by the user. A new approach was taken to integrate the cameras into the system by placing them behind active projection walls, which can be switched from transparent to opaque electrically. Unlike other systems, the cameras are therefore not visible to the user, who thus behaves more naturally. In addition, since the cameras are placed outside of the projection room, there is more space to move inside the immersive environment.

The article describes the technology and functionality of the system, as well as the gathered experiences.

1 Introduction

Advancing globalization and increasing demand for flexibility to quickly react to changing customer needs are influencing the way in which business is done. Short response and development time are key factors for success. Information and communication are the primary competitive tools in the 21st century. Increasing product complexity involves a growing number of people and companies, which are often spread all over the world. As a result, the need for travel and communication is increasing. The Internet and e-mail technologies have opened new avenues for communication. Video conferencing has also been available for over a decade now. But even the combination of all these technologies cannot always replace a face-to-face meeting. Thus, the goal is to realize a new generation of telecollaboration systems where the user’s textures and silhouettes are captured in real time and then represented as a 3D model in the other installation.
First steps have already been taken to use VR for distributed collaboration. Computing tools support information exchange and simple communication fairly well. However, collaboration on complex issues is not well supported. Successful models of computer-supported collaborative work (CSCW) are still rare (Elspass et al., 1999). So far, in virtual meetings, human beings are inadequately represented and disembodied through text, voice, or 2D video projections. The representation of people is therefore not natural. As a result, the level of presence of the remote person is low and the separation between remote collaborator and task can be quite frustrating. Ideally, the remote person should be embodied by a full-size, photorealistic, 3D representation. Such a representation is ideally visualized with Spatially Immersive Displays.

Spatially Immersive Displays (SID) have become increasingly popular over the past decade. They enable the user to work in virtual spaces while being physically surrounded with a panorama of imagery (Lantz, 1996). The most common SID used today is the CAVE from the University of Illinois, Chicago, or one of its variants (Cruz-Neira, Sandin, & DeFanti, 1993). This environment typically comprises a cubic room with up to six back-projection units. Distributed versions of SIDs allow users to interact with remote collaborators in telecollaboration applications. These systems usually integrate 2D video-based human avatars, possibly enhanced with prereconstructed geometric models, into the virtual environments (Gross, Kunz, Meier, & Staadt, 2000). The Cabin of the University of Tokyo is a five-sided SID, consisting of three wall projections, a floor projection, and a ceiling projection (Ogi, Yamada, & Hirose, 1999). In 1997, the Cabin was extended to a networked environment by connecting it to other SIDs to allow telecollaboration. The user is captured with infrared cameras placed on tripods inside the SID. Infrared cameras have been chosen because of the low light conditions inside the SID. A black-and-white representation of the user is then transferred to the remote installations. Immersive projection systems demand high resolution. The resolution of a display wall can be increased by using multiple projectors. For systems with large numbers of projectors, automatic projection calibration is mandatory. In 1998 a display wall was built at Princeton University, using eight LCD projectors. Each projector is connected to a node of a computer cluster and an automatic projection calibration is integrated into the system (Wallace, Chen, & Li, 2003). In November, 2000 the system was scaled up with 24 Digital Light Processing (DLP) projectors (Chen et al., 2002).

While stereo projection has already reached a high level of quality, the acquisition of the user with simultaneous projection is still very challenging. This often results in compromises between acquisition and projection. Infrared cameras are often used due to the poor light conditions inside SIDs. Sometimes the cameras are placed in front of the projection, which therefore decreases the immersion quality and the size of the working area. In some cases, only one camera is used, allowing only a 2D representation of the user.

2 Contribution

In the presented work, the above mentioned issues have been addressed and new solutions have been developed to build the “blue-car” an innovative prototype of a highly immersive projection and video-acquisition virtual environment for collaborative work. The new system makes it possible to record live video streams of users and to simultaneously project virtual reality scenes. In a virtual meeting the participants are embodied by a realistic high-quality representation: fully 3D rendered, and supporting motion and speech in real time (Elspass et al., 1999). In order to increase the immersion, a six channel audio system was also installed. The user, as part of the real world, is therefore synthesized by image and sound and integrated in the virtual world. Thus, the SID evolves from a virtual reality system to an augmented virtuality system.

Special solutions had to be found to allow simultaneous projection and picture acquisition. The cameras are placed behind active projection screens, which can be switched to a transparent state to perform picture acquisition. This solution allows integrating the cameras in a SID without interfering with the projected images. The controversy between darkness for a sharp projection
and brightness for picture acquisition has also been addressed. An active LED illumination in combination with modified shutter glasses has been implemented to allow an acquisition with color cameras while not disturbing the user. The goal of the so-called blue-c installation is to build collaborative, immersive virtual environments, which integrate real humans as three-dimensional objects. Two installations are interconnected to allow bidirectional collaboration and interaction among people sharing virtual spaces. The people are captured in real time, full color, and three-dimensionally. Each installation consists of a projection system and acquisition hardware that operate in the visual wavelength spectrum (see Figure 1).

Essentially two systems must be combined into one installation: an immersive visualization system and an acquisition system. The acquisition has to take place in the visual wavelength spectrum and in full color. Multiple cameras are used which enable a 3D reconstruction of the acquired person. In order to proof the concept of networked collaboration, two setups were realized, located at different sites of the campus.

3 System Overview

As a central element a special projection screen is used that can be switched from opaque to transparent and back. The idea is to use time multiplexing to combine the projection and acquisition. During the opaque state of the projection screen, the projection is running and an image is projected onto the screen. During the transparent state, the cameras can look through the projection screen and take images of the user inside the installation. The switchable projection screen has to be synchronized with the acquisition system. If the screen switches quickly enough between the transparent and opaque states, no flickering will be observable and the cameras will not be visible to the user. Phase-dispersed liquid crystal (PDLC) glass panels are used as a projection screen. The panels are based on liquid crystal (LC) technology and can be switched electrically to transparent and opaque. Although these glass panels are commercially available, they were not primarily designed for projection but rather as an architectural element. Thus, measurements were performed to find out whether they could be used as shuttered projection screens. The maximum available width of the panels is 950 mm. For a projection room of 2.85 m × 2.85 m three of these panels are installed per side.

With the use of actively shuttered projection screens, the projection and acquisition have to take place at different points in time. This time multiplexing between projection and acquisition has two or three different phases, depending on the projection. For a normal monoscopic projection, two time phases are necessary, one for projection and one for acquisition. In combination with an active stereo projection, three phases are required, one for the left-eye projection, one for the right-eye projection, and one for picture acquisition. This sequence is repeated with a frequency, that is high enough to avoid flickering that can be noticed by the user.

An important question was how to illuminate the user without disturbing him or her and without altering the projection quality and the degree of immersion. The illumination has to be in the visible light spectrum since color cameras are used. The solution is to make use of the three phases and to activate a flash illumination only during picture acquisition. As protection from the light, the user has to wear shutter glasses, which are synchronized with the illumination and which are modified by

![Figure 1. Principle of the blue-c.](image-url)
including a third phase, when both lenses for the left and right eye are darkened. These shutter glasses are needed anyway for the active stereoscopic projection. Figure 2 illustrates such a projection sequence, which is followed by an acquisition sequence.

During the third time phase, when both glasses are darkened, an active illumination is triggered. The illumination is preferably done with white light in order to achieve a true-color texture recognition. It is possible to use a strobe light or white light-emitting diodes (LEDs). Figure 3 shows how this active illumination can be kept out of the user’s eyes by integrating a third phase into the shutter glasses (Kunz & Spagno, 2001a; Kunz & Spagno, 2001b).

In the left-hand pair of images in Figure 3 the illumination is shown as seen without the third phase; in the right-hand pair of images, the illumination is shown after the third phase within the shutter glasses is activated. In each pair, the second image shows an object that is only illuminated by ambient light.

With sufficiently bright illumination, it is possible to acquire good-quality images. The cameras for recording the texture of the front of the user have to be placed in front of user without being in his or her field of view (Fuchs et al., 1994). Therefore, the best position for the cameras would be behind the projection screen, where they cannot be seen by the user (Figure 4). The active projection screens allow the cameras to be arranged around the projection room. The layout of the blue-c is a three-sided projection room with a quadratic ground plan. This quadratic layout has been used for the first time in the cave (Cruz-Neira, Sandin, & DeFanti, 1993). No edge-blending is required since the different projections are on different screens.

The working principle of the blue-c relies on an exact synchronization among all components involved. Cameras, flash illumination, shutter glasses, projector shutters, and the active projection screen need a hard synchronization to allow stereoscopic projection together with image acquisition.

The triggering sequence of all components can be seen in Figure 5. The camera triggering frequency is set to acquire images only every seventh cycle of the basic triggering frequency of 62.5 Hz. This corresponds to 8.9 images per second. This value was chosen to allow enough time for the acquisition system to process the incoming images. Although the flash illumination and the triggering of the PDLs could be reduced to 8.9 Hz, we kept the higher triggering frequency in order to avoid flickering that would be disturbing to the user since the human eye is very time-sensitive at lower frequencies.
4. The Components in Detail

4.1 Mechanical Construction

Since a magnetic tracking system was chosen, the basis of the construction is a wooden platform with a total height of 540 mm (see Figure 6). The tracking emitter is built into the middle of the wooden platform and thus, is not visible to the user. The two lower front loudspeakers and the subwoofer are also built into the platform. The floor of the platform can be easily opened to access all the built-in components. The upper structure is built of fiber-reinforced composites (glass and carbon). These are stiff enough to keep the LC projection panels safely in place and, at the same time, still small and attractive from a design point of view. Cable channels are built into the beams, providing sufficient space for the cables of all components placed on the upper part of the structure, including the cables for the active projection screens. Together with the wooden platform there is enough space for all the cables and connectors for the system. The chosen materials, wood and fiber-reinforced composites, assure an accurate functioning of the tracking system. The cables and the loudspeakers, which are at a distance of 1.5 m from the emitter of the tracking system, do not have any important influence on its accuracy. The results from preliminary tests show that the electrically switched glass panes also do not interfere with the tracking system.

4.2 Hardware Construction

Figure 7 gives an overview of all components of the blue-c and its connection scheme. A total of 6 projectors and four monitors are connected to an SGI Onyx. The 16 cameras are connected via sixteen FireWire cables to the computer cluster. The active projection panels, the 6 ferro-electric shutters in front of the projectors, the active illumination, the cameras, and the IR-emitters are synchronized by custom-made synchronization electronics. The individual components will be discussed in the following sections.

4.2.1 Active Projection Screen. Phase dispersed liquid crystal (PDLC) glass panels offer the required features for a switchable projection screen. They can be controlled electrically and can be switched in a few milliseconds or less between a transparent and an opaque state. Different glass manufacturers have switch-
able glass panels available with an integrated PDLC layer. To change the optical property of a PDLC glass panel, an electrical field has to be applied perpendicular to the PDLC film. A voltage in the range of 50 V to 100 V is necessary to generate this electrical field. The PDLC glass panels consist of two glass layers, coated with a transparent electrode on the inside surface, and a PDLC film in between. Each of the two conductors has to be contacted by an electrode. On the glass panels used, the two copper electrodes are located on the two shorter edges so as to be invisible when the glass panels are installed. The current flowing through the transparent electrode has to be limited to avoid its overheating and therefore damaging the PDLC glass panel. The manufacturer recommends not exceeding 300 mA for a 2240 mm × 950 mm panel with the electrodes placed on the short edges as installed in the blue-c. To optimize the synchronization electronics, the electrical properties of the panels have to be analyzed.

In order to analyze the electrical properties of the PDLC panels, the current response to an applied voltage was measured. As with other liquid crystal devices, the PDLC’s should not be exposed to any DC voltage, which could cause ion buildup, damaging the liquid crystal structure. Therefore, only AC measurements were performed. There is also an upper frequency limit due to current limitations. For a voltage of 80 V the maximum frequency is around 100 Hz (Figure 8).

To calculate the electrical behavior of the PDLC glass panels, an equivalent circuit of three components as proposed by Drzaic (1995) is used (Figure 9).

Based on this circuit the complex impedance is:

\[ Z = \left( R_1 + \frac{R_2}{1+(\omega CR_2)^2} \right) - j \left( \omega CR_2^2 \right)^{1/2} \]

This equation has a real and an imaginary part and thus only two of three variables could be calculated. However, since more measurements at different frequencies

Figure 6. The mechanical construction of the blue-c.

Figure 7. Component overview.
were performed, an approximation was calculated, minimizing the mean square error (MSE) between the calculated and the measured voltages. The approximated values are:

\[ R_1 = 174.5 \Omega; \quad R_2 = 2494 \Omega; \quad C = 11 \mu F \]

The electronic control of the PDLC panes can be adjusted to eliminate any DC components in the driving voltage. In addition, an external DC decoupling circuit has been added to guarantee that no DC voltage damages the glass panels, even if a fault in the driving circuit occurs. This DC decoupling consists of a capacitor \( C_{\text{D}} \) and a resistor \( R_{\text{D}} \) (Figure 10). The values are 60 \( \mu F \) for the capacitor and 10 k\( \Omega \) for the resistor.

The glass panes show a very stable performance over time. We do not observe any significant change either in the electrical behavior or the stability of the LC film. The system worked for many days without any problems, although the panes are driven at their upper limit in frequency and allowable current.

### 4.2.2 Projectors and Active Shutters

The active LC projection screens do not support passive stereo projection due to their depolarization properties. Therefore, an active projection system was chosen for the blue channel. In the year 2000, when the design and the construction of the system were started, active stereo DLP projectors were just emerging and still much too expensive for our budget. The state-of-the-art CRT projectors were also still quite expensive compared to the light output. Furthermore, we were looking for a system that could be turned black during the camera acquisition period, that is, 62.5 times per second. The decision was taken to use two three-chip LCD projectors (Sanyo XF12, 3500 ANSI lumen) per side and external LC shutters in front of the projection lens. With these shutters it is possible to generate an active stereo projection by alternating the light output of the two projectors and blocking it during the picture acquisition period.

The two projectors on each side are mounted in a rack for a passive stereo projection installation (Figure 11). The LC shutters are custom-made ferro-electric liquid crystal shutters with an aperture size of 140 mm \( \times \) 140 mm. The shutters are mounted in front of the 1.2:1 projection lenses. This lens allows projection directly onto the projection wall without any additional mirrors. Using no mirrors in the projection path facilitates the alignment of the two LCD projectors for active stereo projection. The shutters do not have to be synchronized with the Onyx and projectors, thus leaving the shutter times completely flexible. This principle would not work with a single-chip DLP projector, since the sequential generation of the three colors by a “color
wheel” would require a complicated synchronization of the shutters with the projectors. However, today, 3-chip DLP projectors could be used instead of the two LC projectors. The shutters in front of the projectors have to be switched on and off at a frequency of approximately 60 Hz.

Twisted Nematic (TN) liquid-crystal shutters, as used in shutter glasses, can offer a contrast ratio of 1000:1 or better (Lipton, 2001). They switch in about 2.5 ms from black to transparent and in less than 1 ms from transparent to black (Lipton, 1991; Woods & Tan, 2002; Bougrioua et al., 2002). Ferro-electric (FE) liquid-crystal shutters offer about the same contrast ratio as TN shutters, but much faster switching times. The FE shutters used in front of the projectors are 140 mm × 140 mm and offer a contrast ratio of approximately 750:1. The switching time from 10% to 90% transparency and from 90% to 10% transparency is below 100 μs (see Figure 12).

The upper measurement in Figure 12 shows the voltage measured on the shutter. The mean value of this voltage is zero, as required. The lower measurement shows the optical response of the shutter, measured by a phototransistor and a light source. The response is very fast and guarantees an excellent separation between the two stereo channels.

A TN shutter switches to black if a voltage is applied and to transparent if the voltage is removed. An FE shutter, in contrast, switches to black if a voltage of one polarity is applied, and to transparent if a voltage of the opposite polarity is applied. It is important that the shutter not be subject to any DC voltage, as it will be damaged. The DC decoupling is achieved by connecting a capacitor \( C_D \) of 1 μF in series and a resistor \( R_D \) of 1 kΩ in parallel to the shutter (see also Figure 10).

Mounting the shutters directly in front of the projector’s lens did not cause temperature problems as expected. Even after several hours of projection the temperature was beneath the limit tolerated by the temperature-sensitive devices.

4.2.3 Active Illumination. The requirements on the blue-c illumination are very demanding. For the projection, both the inside and the outside of the projection room have to be dark. On the other hand, bright illumination is important for good-quality image acquisition. The illumination has a big impact on the quality of the extracted silhouettes and acquired textures. A person inside the blue-c should be illuminated uniformly from all sides and no shadow should be projected on the floor. The illumination has to be directed away from the PDLC glass panels to avoid contrast-loss and reflections.
An active illumination is used to satisfy the needs of both projection and image acquisition. The active light is off during projection and on for the image acquisition. Therefore the light has to provide illumination for only a few milliseconds and must be able to turn on and off with a frequency between 60 and 70 Hz. First, tests were done with a strobe light. A high voltage discharge in a xenon flash lamp produces a bright light pulse of a very short duration. Frequencies in the range of 60 Hz are no problem for this type of lamp. Despite the fast switching, this type of light has some important disadvantages. First, light is emitted for only a few milliseconds. The light intensity integrated over time is therefore only mediocre. In addition, the high voltage discharge in the very short time period causes heavy electromagnetic pulses, which can interfere with surrounding electronic components. The discharges also cause a disturbing acoustic noise. Finally, the strobe light is focused in one spot. This is a handicap when trying to distribute the light uniformly in the projection room. All these disadvantages led us to look for other illumination solutions.

The requirement of short switching times restricts the number of suitable light sources considerably. Light-emitting diodes (LEDs) have very short switching times and are thus suitable for our application. Today, white LEDs are commonly available and the light efficiency is about twice that of an incandescent bulb (Zorpette, 2002). LEDs can be easily grouped in clusters to give more light output. The clusters are flat, can be of any shape, and the light output can be distributed homogeneously over the cluster if desired. A total of 9,984 white 5 mm LEDs have been integrated into the blue-c. The opening angle (50% intensity) is 50 degrees and the light output is approximately 2,200 mcd per LED. These LEDs were the brightest available on the market in 2002. The LEDs are configured into 32 clusters, each containing 312 LEDs. The clusters are reassembled in groups of two, four, or five and mounted in long aluminum profiles.

The LED clusters have to be placed carefully in the blue-c to allow a good quality image acquisition. The cameras are mostly placed outside the blue-c and face more or less horizontally to the user through the PDLC glass panels. Under this aspect a diffused frontal illumination of the user would be the most suitable. But a frontal light would also shine directly into the opposite cameras and, furthermore, would put too much light on the glass panels, making them appear gray. In addition, it would be difficult to find a place to mount the clusters without interfering with the projection and the cameras.

The solution is to distribute the LED clusters along the upper and lower edges of the projection room. The LEDs can be adjusted in such a way that they completely illuminate the user, minimizing at the same time the amount of light being directed at the glass panels and at the opposite cameras. The additional mask in front of the LEDs helps to further diminish the amount of scattered light reaching the glass panels. Figure 13 shows a person between two opposite projection walls, as is the case in the blue-c for the two sidewalls. The light is coming from all four edges and most parts of the person are illuminated by more than one light source. Figure 14 shows one illumination cluster. Five of them are integrated in the aluminum profile and placed at the edge between the floor and the left glass panels.

Realizing the illumination with the diodes, it turned out that the specifications of the LED were not reached by every single element. This resulted in failures and thus in nonactive LED lines in the cluster. After the cur-
rent through the entire cluster was reduced this problem disappeared.

4.2.4 Cameras. Sixteen FireWire cameras are placed around the blue-c on a special aluminum structure. The structure is based on standard aluminum elements and offers the maximum flexibility in the placement of cameras and other components. Each camera is connected via FireWire to one node of the PC cluster. The signal is amplified every 5 m with a repeater. Up to three repeaters are used for each camera.

Dragonfly™ cameras are used since they offer good sensitivity and a high picture acquisition frequency of up to 15 Hz. However, cameras with an even higher sensitivity would be useful in order to reduce the intensity of the flash illumination. On the other hand, the picture acquisition frequency is high enough, since the bottleneck is in the processing of the acquired images. Initial tests showed that a repetition frequency of 10 Hz seems to be sufficient for collaborative work.

4.2.5 Synchronization Electronics. The synchronization electronics of the blue-c were built modularly to offer flexibility in adding and changing components. The main module is the frequency-control module, which is equipped with a reprogrammable PIC 16F877 microcontroller. This module generates the triggering sequence to drive the other modules of the synchronization unit. Three PDLC glass panel driver modules, two shutter, driver modules, and one trigger-interface module are integrated into the synchronization unit, together with the synchronization control module. The LED driver and IR-emitter driver are placed outside of the synchronization unit and are triggered by the trigger interface module.

Figure 15 gives an overview of the synchronization electronics. All modules of the synchronization unit are interconnected with a data bus. In addition, a power bus is integrated into the unit to supply the different modules with the required voltages. The LED driver and IR-emitter driver are located outside of the synchronization unit, together with their own power supplies, to reduce electromagnetic interference caused by the currents.

Using a microcontroller for the synchronization of all components proved to be crucial. Since every component, including identical parts, behaves slightly differently (e.g., the glass panes), it is easy to create individualized triggering signals using the microcontroller. This makes up for the increased effort of installing and programming the processor.

4.2.6 Frequency Control Module. The frequency control module is based on a PIC 16F877 microcontroller. This microcontroller can be reprogrammed in-circuit, that is, without unplugging the chip from the board. Twenty-two input–output ports of the microcontroller are mapped to the data bus. They
can be set individually as outputs or inputs. Each of these ports is connected to a LED to show its state. The microcontroller is clocked with a frequency of 20 MHz to offer high timing accuracy.

4.2.7 PDLC Glass-Panel Driver Module. To drive the nine PDLC glass panels, a total of three glass-panel driver modules are used (see Figure 16). In each case, three glass panels in parallel are connected to the two outputs of a module. The two outputs of a module can be switched separately to either 8 V or 85 V. If both outputs are switched to the same value, no voltage is applied to the glass panels. If the outputs are switched to different values, a voltage of \(+\)77 V or \(-\)77 V is applied to the glass panels in series with the decoupling capacitor. Each of the two outputs is switched directly by the corresponding input coming from the data bus. A current-limit control is superimposed on the voltage switching.

Figure 16 shows a simplified circuit consisting of a PDLC glass-panel driver module connected to three glass panels with their DC decoupling circuits. Each of the two incoming TTL signals switches an optocoupler output to a preset voltage of 8 V or 85 V. The two outputs of the optocouplers are connected to two APEX PA46 operational amplifiers. The APEX PA64 has an integrated, adjustable current-limit control and can run at voltages up to 150 V and currents up to 5 A. The operational amplifiers are used as followers; thus, the input voltage is mapped directly to the output as long as the current-limit is not exceeded. The PDLC glass-panel driver modules are connected to a 95-V power supply. However, the outputs of the module have been set to switch only between 8 V and 85 V. This gives enough margin to the output voltage from the power supply and ground to avoid saturating the operational amplifier. The current-limit of the operational amplifier is set to 900 mA, which corresponds to a current-limit of 300 mA per panel.

4.2.8 Shutter Driver Module. The shutter driver module also has two inputs and two outputs. It consists of two independent circuits with an optocoupler and a half-bridge consisting of two MOSFETs and a half-bridge driver (Figure 17). The optocoupler is used to protect the other modules of the synchronization electronics in case a fault occurs in this module or in a connected component. The output of the optocoupler is connected to a half-bridge driver (IR2111) that drives two MOSFETs. The bridge driver ensures that the two MOSFETs in the half-bridge are never turned on at the same time. The two half-bridge outputs switch the voltage rail-to-rail without any current-limit. In order to drive the ferro-electric shutters, the module is operated with a voltage of 12 V. Three shutters are connected in parallel between the two half-bridges of a module. The two half-bridges are always switched to opposite states. The bridge voltage is therefore either 12 V or \(-\)12 V, as required by the shutters for switching.

4.2.9 Trigger Interface Module. The trigger-interface module is a multifunctional module. It allows a choice between up to 8 lines out of the 22 data lines on the bus. Each line can be connected to a 5 V or 12 V
driver and configured as input or output. For the blue-c all channels used were configured as 5-V outputs. One channel is used to trigger the FireWire cameras. A second one is used to trigger the LED illumination. Two more channels are used to synchronize the shutter glasses and are connected to the IR-emitter driver.

4.2.10 LED Driver. A total of 9,984 LEDs are installed in different clusters in the blue-c. The LED clusters have to be driven with a voltage of 37.5 V and a total current of up to 25 A. The power supply for the LED cluster is installed in the floor of the blue-c and connected directly to the LED clusters. This reduces the wiring distances of the high-current connections and thus the probability of electro-magnetic interference. Each cluster has an integrated MOSFET to switch the LEDs on and off. The triggering signal comes directly from the trigger-interface module.

4.2.11 Shutter Glasses. The LED illumination is triggered 62.5 times per second. The user does not see any flickering because this frequency is above the temporal resolution of the human eye. However, the bright light inside the blue-c diminishes the contrast of the projected image considerably. To protect the user from the active light, an apposite third phase has been integrated into the stereo glasses to keep the light out of the user’s eyes. The projection of the images for the left and the right eye are followed by a third phase, in which both LC shutters of the shutter glasses are darkened. The LED illumination is on only during this phase. This helps to fade out most of the light from the illumination.

In the blue-c we use the NuVision 60GX shutter glasses from MacNaughton. The shutter glasses and the IR-emitter have a built-in microcontroller. We have reprogrammed it to include the third phase. Like most shutter glasses, the NuVision use twisted nematic LC shutters. The transparent-to-black transition time of these shutters is quite fast, while the black-to-transparent switching time takes considerably longer. Figure 18 shows the switching time of the NuVision shutter glasses. The upper measurement shows the transparency of a shutter, where a high value corresponds to a high transparency. The lower measurement shows the voltage applied to the IR-emitter. As can be seen from the measurement, there is no significant delay between sending a signal to the emitter and the beginning of the switching response. However, the switching time from 10% to 90% transparency takes approximately 3.3 ms, while the switching from 90% to 10% transparency takes about 0.5 ms. These values correspond to the values measured by Woods and Tan (Woods & Tan, 2002) with other shutter glasses. For practical use there is a work-around involving some blanking time between the projections for the left and right eye.

5 Overall Setup

Two complete collaboration setups were designed, as shown in Figure 19. In the upper image in Figure 19, the first prototype is shown, essentially a laboratory setup. One lesson learned from this is that in many cases only the front screen is used for collaboration. This allows for the creation of a more design-oriented setup in a public room (as shown in the lower part of Figure 19) using only a single screen. Since the camera positions are known from the first prototype, there was no longer any need for a flexible installation.
The goal of the second setup (bottom image in Figure 19) was thus not to reproduce the first installation, but rather to create an asymmetric installation for the collaboration. With the asymmetric setup, applications were first created, transferring 3D sound and 3D images of the people from one installation to the other. Figure 20 shows a simple collaboration between two individuals engaged in a dialogue. Each person is in an installation at a different location on the campus.

Since the first system is an experimental setup, a long initialization time was required before the collaboration could start. Thus the system is not used for hands-on collaboration yet. Further work will shorten the initialization phase and will allow easier access to the system.

6 Conclusions

The active projection screen is driven at its physical limits. The transition time from opaque to transparent (10% to 90%) takes approximately 2 ms, while the transition from transparent to opaque (90% to 10%) takes approximately 6 ms. The slow transition from transparent to opaque is dictated by the internal relaxation forces of the LC film and cannot be accelerated electrically. This non-ideal behavior can be minimized by optimizing the time pattern of the different components. For the user, just the hotspot of the projectors becomes a little more evident, but it remains at an acceptable level. The active projection screens offer a very bright and homogenous image.

The junctions between the three projection-screen panels are visible but not disturbing. The LC film of the active projection panels is installed between two glass panels. The surface of these glass panels is treated with an antireflective coating. Nevertheless, some reflections from the other projection screens are evident. The reflection can be compared to the reflection on a CRT television in a medium-bright illuminated room. The reflection is noticeable when the user concentrates on it and disappears as soon as he or she concentrates on the application. Since the projectors are darkened during the transparent state of the projection screens, the camera acquisition is not disturbed by any reflection. The cameras are positioned in such a way as to see the user’s entire body, even if the user gets very close to the projection screens.
The channel separation of the stereoscopic projection is very good, and the total performance of the projection is convincing. The brightness is higher than traditional CRT stereo projectors at a lower price per stereo projection rack. The six-channel audio system proved to be very powerful. The user can precisely localize a simulated noise or sound source. The subwoofer located in the wooden platform is also important for good audio performance. In addition, it can transmit vibrations to the user at lower frequencies, and this acoustic stimulus plays an important role in high immersion.

The mechanical structure was shown to meet the required demands. Its stability and rigidity give a strong sense of confidence in the blue-c. The user is never uneasy about touching the projection screen or walking around, as in some other VR installations. The flexibility in the placement of new components and cables, as well as the quick access to all the components, proved to be a very valuable feature of the blue-c construction.

7 Further Work

The two setups showed that collaboration over a network using 3D representations is technically possible. However, there are more problems to overcome. In its technical aspects, the system should be downsized in cost and weight, with the goal being a mobile installation. Here new stereo projection systems would also be tested that are easier to install and adjust. Also new projection materials, such as active Perspex, will be evaluated. As a first step in this direction we will build a demonstrator that would be suitable for presentations on conferences and exhibitions. The demonstrator could be used to show the core technology of the blue-c itself, but also as another input station for a multipoint collaboration (Disz, Papka, Pellegrino, & Stevens, 1995; Lehner & DeFanti, 1997; Fuchs et al. 2002; Bailett, Calahan & McCluskey, 1998).

Further work on the blue-c will also deal with implementing the technology in existing processes, for instance, the product development process or the education process. Thus applications for the blue-c will be generated that offer benefits to the user when using the 3D capability in collaborative work. Further information can be found at: http://blue-c.ethz.ch.

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