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IMMERSIVE VR PROJECTION SYSTEM WITH SIMULTANEOUS IMAGE  
ACQUISITION USING ACTIVE PROJECTION SCREENS

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# ABSTRACT

The “blue-c” project was an internal research project of the Swiss Federal Institute of Technology with the goal to build collaborative, immersive virtual environments which integrate the representation of real humans as three-dimensional objects. The first of the two installations that were built is a three-sided spatially immersive back projection system. Sixteen cameras are integrated in this installation in order to capture the silhouette and texture of the user. A 3D-representation of the user is generated in real time and transferred to the remote installation, where it is combined with the virtual world and presented to the remote user. The remote user is also captured with sixteen cameras and his 3D-representation is transferred back to the first installation. The interconnected installations enable multiple users to interact and share applications simultaneously. The possibility to see the remote user in conjunction with the application gives a high sense of presence.

This thesis covers the hardware component of the “blue-c” project, namely the spatially immersive projection system and the image acquisition system. The main challenge associated with the hardware was to combine the projection with the image acquisition. In order to meet this challenge, electrically switchable “phase dispersed liquid crystal (PDLC)” glass panels are used as projection walls. The panels are switched to transparent for acquisition and opaque for projection. The switching is repeated 62.5 times per second. The cameras, which are located outside of the projection room, can acquire an image of the user through the PDLC glass panels during the transparent states. The active stereo projection system is only active when the glass panels are opaque.

The switchable projection screens are discussed in this dissertation. The properties of the PDLC glass panels are analyzed, including the electrical and the projection properties. The triggering signals, which drive the glass panels, are optimized to minimize the switching times.

An active LCD stereo projection system was developed to enable stereo projection in conjunction with image acquisition. Each projection side includes two LCD projectors and two ferroelectric shutters. The timings for the left and right eye projection as well as the blanking of both projectors during image acquisition are selectable.

A bright illumination with a homogenous light distribution is necessary to facilitate the silhouette extraction and the texture acquisition. On the other hand, a dark surrounding is advantageous for a good immersion. Therefore an active illumination consisting of 9,984 LEDs is used, which is switched on and off 62.5 times per second. The illumination is only on during image acquisition. Modified shutter glasses are used to keep the light away from the user. This is achieved by blocking both shutters of the glasses during image acquisition.

In order to synchronize all active components of the projection and acquisition system, a dedicated synchronization electronics system was built. A microcontroller is integrated into the electronics to facilitate quick adaptation of the triggering timings. Different driver modules provide the driving signals for the different components.

The mechanical construction of the spatially immersive projection room consists of fiber reinforced composites (glass and carbon) and wood. The selected materials do not

X

interfere with the electromagnetic tracking system and the design supports the full functionality of the projection and image acquisition system.

# KURZFASSUNG

Im Rahmen des ETH Forschungsprojektes “blue-c“ wurden kollaborative, immersive virtuelle Umgebungen aufgebaut, welche Personen als dreidimensionale Objekte erfassen und integrieren. Die erste der zwei gebauten Anlagen basiert auf einem dreiseitigen immersiven Rückprojektionsraum. 16 Kameras sind in der Installation integriert und erfassen die Silhouetten und Texturen des Benutzers. Eine 3D-Repräsentation des Benutzers wird, basierend auf den 16 Kamerabildern, in Echtzeit erzeugt und dann zur gegenüberliegenden Installation übertragen. Dort wird das 3D-Abbild in die virtuelle Umgebung integriert und zusammen mit dieser projiziert. Der Benutzer der gegenüberliegenden Installation wird ebenfalls mit 16 Kameras erfasst und sein 3D-Abbild wird zurück zur ersten Installation übertragen. Die untereinander verbundenen Installationen ermöglichen gemeinsames Arbeiten in einer Applikation. Die gleichzeitige Visualisierung des Arbeitspartners zusammen mit der Applikation erzeugt ein hohes Mass an Präsenz.

In der vorliegenden Doktorarbeit wird auf die Hardwarekomponenten und den mechanischen Aufbau des kollaborativen, immersiven Visualisierungsraumes eingegangen. Dies umfasst die gesamte Projektionseinrichtung sowie das Bildaufnahmesystem. Die grosse Herausforderung besteht in der simultanen Projektion und Bildakquisition. Elektrisch schaltbare “Phase Dispersed Liquid Crystal (PDLC)“ Glasscheiben werden als Rückprojektionswände eingesetzt. Diese werden transparent geschaltet, wenn die Kameras Bilder aufnehmen, und dagegen matt geschaltet während der Projektion. Dieser Schaltvorgang zwischen transparent und matt wird 62.5 mal pro Sekunde wiederholt. Im transparenten Zustand nehmen die Kameras, welche ausserhalb des Projektionsraumes aufgestellt sind, Bilder der Person im Innern des Projektionsraumes durch die Scheiben hindurch auf. Das Stereoprojektionssystem ist nur aktiv während des matten Zustands der PDLC-Scheiben.

Das Verhalten der schaltbaren Projektionsscheiben wird ebenfalls in dieser Dissertation untersucht. Hierbei wird sowohl auf das Projektionsverhalten als auch auf die elektrischen Eigenschaften eingegangen. Das Ansteuersignal zum Schalten der PDLC Scheiben ist optimiert worden, um kurze Schaltzeiten zu erzielen.

Im Rahmen dieser Arbeit wurde ein aktives LCD Stereoprojektionssystem entwickelt, welches die simultane Projektion und Bildaufnahme ermöglicht. Im dreiseitigen Projektionsraum stehen drei solcher Systeme im Einsatz. Jedes der drei Systeme besteht aus zwei LCD Projektoren und zwei ferroelektrischen Shuttern. Die Zeitdauer der Projektion für das linke und rechte Auge sowie die Schwarzphase während der Bildaufnahme kann beliebig eingestellt werden.

Eine helle und gleichmässige Beleuchtung ist unabdingbar, um qualitativ gute Silhouettenerkennungen und Texturaufnahmen zu ermöglichen. Auf der anderen Seite sollte der Raum möglichst dunkel sein, um eine kontrastreiche und immersive Projektion zu gewährleisten. Eine aktive Beleuchtung, bestehend aus 9'984 weissen LEDs, wird hierzu verwendet. Die Beleuchtung ist nur während der Bildaufnahme aktiv. Um das Licht von den Augen des Betrachters fernzuhalten, werden modifizierte Shutterbrillen eingesetzt. Beide Shutter der Brille sind dunkel geschaltet, solange die Beleuchtung aktiv ist.

Um alle Komponenten zu synchronisieren, wird eine eigens dafür entwickelte Synchronisationselektronik verwendet. Ein eingebauter Mikrokontroller ermöglicht eine flexible Anpassung der Schaltzeitpunkte der einzelnen aktiven Komponenten.

Der mechanische Aufbau des immersiven Projektionsraumes besteht aus Faserverbundwerkstoffen (Glas und Kohlenstoff) sowie aus Holz. Die gewählten Materialien gewährleisten eine ungestörte Funktion des elektromagnetischen Trackingsystems. Das Design des Aufbaus wurde auf die funktionalen Anforderungen der Projektion und Bildaufnahme hin ausgelegt.

# INTRODUCTION

This chapter describes the context and the background of this thesis.

## 1.1 MOTIVATION

Advancing globalization and the increasing demand for flexibility to react quickly to changing customer's 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 21<sup>st</sup> century. The overall increasing product complexity involves a growing number of people and companies, which are often spread across the whole globe. As a result, the need for traveling and communication has increased. The internet and e-mail technologies have opened up new methods of communication. Video conferencing has been available for over a decade now. However, even the combination of all these technologies cannot always replace face-to-face meetings.

Computer power and electronic storage capacity is increasing every year. Three-dimensional (3D) CAD data is widely available in many companies and is used for most complex projects [46]. Some companies already use Virtual Reality (VR) systems for visualizing CAD data. The increasing amount of electronic data available in companies, comprising development and production processes data, is already improving long-distance collaboration. Despite this, communication within companies and between business partners still has the potential to be improved. The question arises regarding how the new visualization technologies, computer power and the growing availability of 3D data can be used to improve communication. Is there a way to use Virtual Reality (VR) for communication in day-to-day business?

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 by these tools. Successful models of computer supported collaborative work (CSCW) are still rare [28]. Thus far in virtual meetings, humans are inadequately represented and disembodied through text, voice or two-dimensional (2D) video projections. The representation of the human is therefore unnatural. As a result the level of presence of the remote person is low and the separation

between the remote collaborator and the 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 (SID).

Particularly in the field of product development the need arises to have a communication tool, which goes beyond the classic video conferencing systems. The product development process consists of many different phases, which involve a large number of teams, which are sometimes spread all over the world. The different phases include clarification and specification of the conceptual formulation, finding functions, searching for solution principles, classification into realizable modules, structuring the modules and layout of the product, to mention just a few of them. Computer tools are used to support most of these developmental steps. With increasing product complexities, parallelization of different product development steps has become necessary in order to reduce the development times. Communication plays a key role in such a distributed product development process. The need arises to have a virtual meeting room, where distant development partners can meet ad hoc, without the inconvenience of time-consuming traveling. This virtual meeting room should support speech, gesture and mimic in order to allow communication at a high level of presence. This would enable natural communication, including social communication aspects and therefore permit the participants to focus, with a high level of efficiency, on the task which needs to be solved. In addition, the virtual meeting room should enable the display of information and product data as needed. The visualization of the product data and of the remote users should be simultaneously and naturally integrated amongst each other. Existing video conferencing systems poorly integrate information and product data with the image of the remote person. In addition, many small but important communication details of a face to face meeting, including social aspects, are not supported by most video conferencing systems.

## 1.2 RELATED WORK

Spatially Immersive Displays (SIDs) 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 [25]. The most common SID used today is the CAVE™ from the University of Illinois, Chicago, or one of its variants [6]. 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 2-D video-based human avatars, possibly enhanced with pre-reconstructed geometric models, into the virtual environments [26].

A different approach to construct dedicated SIDs is to integrate the projection units and the projection surfaces directly into existing office environments as it has been done in the “Office of the Future” [15]. For this project, cameras are placed in the ceiling and the walls of the office to allow telecollaboration. They use 2D video-based avatars and speech for interpersonal communication.

TELEPORT [14] uses special dedicated visualization rooms for teleconferencing. The essential idea behind TELEPORT is termed, co-presence: the illusion that remote conference participants, although actually distant, are present in the local participant’s physical space. Each of the interconnected installations use a stereo projection unit and a single camera placed on a table in front of the user. The 2D imagery along with the video texture of the remote participant is then placed in the 3D model of the remote office.

At the MIT Media Lab a silhouette-based interactive dual-screen environment named SIDEshow has been developed [29]. The system extracts a silhouette of the participant to drive an interaction. An IR-camera, attached to the bottom of a screen, captures the silhouette of the user. The background is illuminated with infrared light to provide a good contrast.

In the EU, the Information Societies Technology (IST) project- VIRTUE (Virtual Team User Environment) focuses on immersive 3D video conferencing systems [52]. Each of the installations integrates a large scale 2D display for visualization. Four cameras are mounted on the edges of each display and a virtual camera view is generated from the four captured images [53]. The color image of the remote user can be observed from different points of view. However, no stereo projection system or display is used.

The Cabin of the University of Tokyo is a five-sided SID, consisting of three wall projections, a floor and a ceiling projection [12]. 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 were chosen because of the low light condition inside the SID. A black and white representation of the user is then transferred to the remote installations.

Most SIDs use stereo projection to give the user a high degree of immersion. To generate the stereo effect, eclipse or polarized technology is used. The Televue system [20] which was created in 1923 was the first commercial application of eclipse technology for motion pictures (also known as active stereo projection or field-sequential stereo projection). However it was not until 1984 that the field-sequential stereoscopic displays started to become more popular with the commercialization of LC shutter glasses by StereoGraphics [19]. There are many different topics within the area of stereo projections, which provide the content of many publications, for example, [21], [22], [23], [18], [27].

Immersive projection systems demand a high resolution. The resolution of a display wall can be increased by using multiple projectors. For systems with large numbers of projectors, an automatic projection calibration is necessary. At the University of Princeton a display wall was built in 1998, using eight LCD projectors. Each projector is connected to a node of a computer cluster and an automatic projection calibration is integrated [49]. In November 2000 the system was scaled up with 24 DLP projectors [50].

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 low 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, which only allows for a 2D representation of the user.

### 1.3 CONTRIBUTION

The goal was to build a system which enables collaboration and communication among people who are at geographically different locations with a high level of presence. The following challenges needed to be met. The person has to be acquired in 3D with full textures and colors. At the same time, the person from the remote installation has to be visualized in 3D without interfering with the acquisition system. The application, for

example a visualization of an assembly line, has to run simultaneously with the conferencing component of the system. The images of the remote person and the visualization from the application have to be combined and presented on the same visualization system.

In the presented work, the aforementioned issues have been addressed and new solutions have been developed to build an innovative prototype of a highly immersive projection and video acquisition virtual environment for collaborative work [41]. With the new system it is possible to simultaneously record live video streams of users and to project virtual reality scenes. This enables a number of participants to interact in a virtual meeting, represented as completely as possible: fully 3D rendered, supporting motion and speech in real time [28]. The user, as part of the real world, is therefore synthesized 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 enable simultaneous projection and picture acquisition. The cameras are placed behind active projection screens, which can be switched to a transparent state for picture acquisition. This solution enables the cameras to be integrated into a SID without interfering with the projected images. In addition, finding a balance between darkness which is needed for a sharp projection and brightness for picture acquisition was addressed. An active LED illumination in combination with modified shutter glasses was implemented to allow an acquisition with color cameras without disturbing the user.

## 1.4 BLUE-C PROJECT CONTEXT

The presented work was carried out within the context of the blue-c project. In this project a novel hard- and software system was created that successfully combined the advantages of a CAVE™-like projection environment with simultaneous real-time 3D video capturing and processing of the user. As a major technical achievement, users can now become part of the visualized scene while keeping visual contact with one another. Consequently, these features make the system a powerful tool for high-end remote collaboration and presentation. Thus far, two portals have been implemented with complementary characteristics, networked with a gigabit connection. One portal is located at the ETH main campus, the second at ETH Hoenggerberg. Various applications have proved the concept and demonstrated the usefulness of blue-c.

Figure 1.1 shows the ETH main campus blue-c portal in action. It is a three-sided CAVE™-like portal with actively shuttered projection walls.



**Figure 1.1** blue-c portal at the ETH main campus

The second blue-c installation, located at ETH Hoenggerberg, is a single projection wall setup (Figure 1.2). Therefore this installation requires less demanding solutions for the simultaneous projection and acquisition than the first installation. Both systems acquire the 3D video inlay with 16 cameras and have stereo projection capabilities.



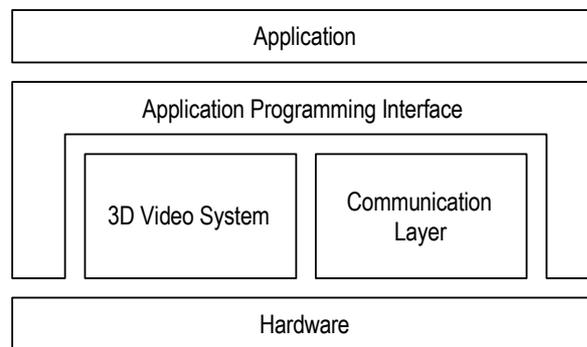
**Figure 1.2** blue-c portal at ETH Hoenggerberg

The blue-c project was organized as an ETH internal research project. It started on May 1, 2000 and lasted for three years. Four ETH research groups participated in this project, namely the Computer Graphics Lab (CGL) under the supervision of Prof. Markus Gross, the Computer Vision Laboratory (CVL) under the supervision of Prof. Luc Van Gool, the

Center of Product Development (ZPE), which is part of the Institute of Mechanical Systems (IMES) under the supervision of Prof. Markus Meier and the chair of Computer Aided Architectural Design (CAAD) supervised by Prof. Maia Engeli at the beginning of the project and later supervised by Prof. Ludger Hovestadt.

The CGL directed the project and was responsible for the core software components, including graphics rendering and 3D video processing, as well as for the computing and networking infrastructure. The CVL was responsible for the silhouette extraction on the captured images and of the camera calibration. The ZPE was responsible for the hardware and projection setup, including the construction of the first blue-c portal at the ETH main campus. The CAAD chair investigated applications and interaction techniques, designed the virtual reality installations and built the second blue-c portal at ETH Hoenggerberg.

Figure 1.3 illustrates the framework of the core components of the blue-c project. In the following section these core components are briefly described.



**Figure 1.3** Framework of the blue-c system

**Hardware.** The hardware includes the projection system, the integration of the acquisition system, the illumination and the synchronization electronics for all the components. The hardware has to satisfy the contradicting needs of projection and image acquisition. The blue-c hardware is the subject of this thesis.

**3D Video System.** The 3D video software computes a 3D representation of the acquired persons from inside a blue-c installation in real-time. The software first builds a 3D point cloud from multiple camera video streams. The point cloud can then be efficiently encoded and streamed to a remotely located blue-c portal where it is rendered into the application. The 3D video system is described in detail in Stephan Würmlin's thesis [1].

**Communication Layer.** The acquisition and rendering systems of the distributed installations are connected with each other and thus enable telecollaboration applications. Strict temporal and bandwidth constraints have to be met in order to enable high quality collaboration with live video streams. Furthermore, the system needs to adapt to changing qualities of the network services. The communication layer is detailed in Edouard Lamboray's thesis [2].

**Application Programming Interface.** The blue-c Application Programming Interface (blue-c API) exposes the blue-c system functionality to the application developer. It provides a rapid application development environment which supports tele-collaboration and the integration of multimedia data into the virtual world. The blue-c Application Programming Interface is the subject of Martin Naef's thesis [3].

**Application.** The applications run on top of the blue-c API and are customized to the requirements of the specific hardware and software layout of blue-c in order to make use

of the full potential of this new system. Two application areas have been researched in the framework of the blue-c project. Infoticles is a novel information visualization metaphor which uses the motion characteristics of particles to explore unexpected data patterns in large, time-varying datasets. This visualization technique is described in detail in the thesis authored by Andrew Vande Moere [4]. IN:SHOP is the first application to investigate and analyze the possibilities of integrating the blue-c technology into buildings. A novel approach to distributed shopping in a new interactive space is introduced. Physical shopping floors are connected and extended into virtual and remote spaces. The impact of video stream systems on architecture is described in detail in the thesis written by Silke Lang [5].

blue-c is the name for the project, as well as the different installations, which have been realized during this project. In this thesis the project will always be referred to as the “blue-c project” and the first installation realized at the main campus will be referred to as “blue-c”.

## 1.5 OUTLINE OF THE THESIS

The thesis is structured as follows:

- ◆ Chapter 2 begins with the requirements list for the blue-c hardware. Based on these requirements, different implementation options are presented and evaluated. The chosen solutions are then discussed in detail. This chapter sets the basis for the following chapters.
- ◆ Chapter 3 focuses on stereo projection systems. In order to set up an immersive projection system it is essential to understand the human visual perception. This is addressed at the beginning of this chapter and is followed by a comparison of different projection systems. The most suitable system for blue-c is then discussed in detail.
- ◆ Chapter 4 discusses the active projection screens, which are a core component of the blue-c hardware. The physical, optical and electrical properties are analyzed.
- ◆ Chapter 5 describes the flash illumination and the modified shutter glasses.
- ◆ Chapter 6 contains the description of the synchronization electronics. The hardware components, which are the contents of chapter 3 to 5, are synchronized amongst each other with these electronics. The graphical user interface to program the different timings is also presented in this chapter.
- ◆ Chapter 7 illustrates the mechanical construction of blue-c. The evolution of the architectural design as well as the integration of the different components is part of this chapter.
- ◆ Chapter 8 contains measurements and experimental results of the blue-c hardware. The triggering timings of the different components are discussed. The advantages and the limits of the implemented system are laid out.
- ◆ Chapter 9 summarizes the conclusions of this thesis and points out further research directions.
- ◆ Appendix A shows a selection of design studies of blue-c.
- ◆ Appendix B includes the schematics of the synchronization electronics.



## CONCEPT

The goal of the blue-c project was to build collaborative, immersive virtual environments, which integrate the representation of real humans as three-dimensional objects together with virtual objects into one common virtual workspace. Two installations are interconnected to allow bi-directional collaboration and interaction between people sharing virtual spaces. The shape and textures of the participants are captured in real time, in full color and three-dimensionally. Each installation consists of a projection system and acquisition hardware, both of which operate in the visual wave length spectrum. Simultaneous projection and picture acquisition are important features of the blue-c project. The immersive projection has to be combined with high fidelity picture acquisition. Several different concepts were evaluated before choosing the implemented solution.

### 2.1 REQUIREMENTS ON AN IMMERSIVE COLLABORATION SYSTEM

Essentially two systems have to be combined into one installation, an immersive visualization system and an acquisition system. The image acquisition has to take place in the visual wave length spectrum and in full color. Multiple cameras are used, which enable a 3D reconstruction of the acquired person. For blue-c it was decided to use sixteen cameras because this number is a good compromise between number of view points and computing complexity. Simulations and tests with different camera configurations, done by the Computer Graphics Lab, were at the origin of this decision. The requirements for the installation are listed in Table 2.1.

The cameras are located around the working area to give full coverage of the user inside the installation. New hardware and software acquisition concepts were developed in the blue-c project therefore it was not possible to define exact camera positions at the beginning of the construction (requirement no. 2). The cameras have to acquire the user from a defined distance in order to capture the entire person. This distance depends on the camera lens which is used. In addition, the person should always be within the focal length of the cameras. Therefore the user should never be too close to the camera (requirement no. 5).

**Table 2.1** Requirements list for the blue-c installation

No.	Requirement	Value, Range, Characteristic	Unit
1	number of cameras to be installed	16	[pieces]
2	positions of cameras in relation to the users	equally distributed around the user, exact position not defined, has to be kept variable	
3	vertical position of the cameras in relation to the user's eyes (standing person, 1.7 m high)	+/- 1	[m]
4	number of overhead cameras (vertically over the user)	1	[piece]
5	lens distance to user	$\geq 1$	[m]
6	camera type to be installed	color camera	
7	camera for silhouette acquisition	same camera used for texture acquisition	
8	triggering of cameras	all cameras have to be synchronized among themselves	
9	system compatibility to camera frame rate	30 and lower	[1/sec.]
10	cameras in front of the projection	none	
11	projection type	stereo	
12	horizontal field of view (FOV) of the projection	$\geq 180$	[°]
13	simultaneous projection and picture acquisition	within one frame latency	
14	illumination color	white	
15	illumination type	bright enough for acquisition, not interfering with projection	
16	design of installation	representative	
17	flexibility of installation	high (prototype, changing needs expected after construction)	
18	room size for user (L x W)	$\geq 2.7 \times 2.7$	[m]
19	maximum size of installation including all components (L x W x H)	$\leq 10 \times 12 \times 4.5$	[m]
20	components to be integrated in the system	tracking, cameras, illumination, loudspeakers, IR emitters, projectors, screens, synchronization unit	
21	construction material	non-magnetic	
22	interference between components	none	
23	static loading capacity of user platform	1,000	[kg]

For the 3D reconstruction of a person, it is important that both silhouette and texture are acquired with the same cameras at the same time (requirement no. 7). Any divergence in time or position would increase the complexity of reconstruction. In addition, all the

cameras have to be synchronized with each other (requirement no. 8). The blue-c system should allow different acquisition frame rates up to a frequency of 30 Hz, which is the maximum camera acquisition frame rate (requirement 9).

Immersion is a necessary quality of a highly functional VR system. A high degree of immersion means that the user is fully integrated in the virtual world, in the best case the user should not be able to distinguish between the real and the virtual world anymore. The degree of immersion is influenced by different parameters. One of such parameters is the field of view (FOV) which describes how much of the viewing area is covered by a display or a projection screen. In general, a wide FOV improves the feeling of immersion (requirement no. 12). A dark environment around the projection also helps to improve the degree of immersion. In this case, the real world, including the projection room, becomes less visible. A stereo projection or display gives participants the illusion that objects are coming out of the projection plane, this is a feature which also contributes to the immersion (requirement no. 11).

The illumination is an important part of the system and has to satisfy different requirements. A bright and homogeneous white illumination is suitable for acquisition whereas dark surroundings are required for an immersive projection (requirement no. 14 and 15).

Considering all the cameras integrated in blue-c, a vision-based tracking system would be a logical consequence. However due to the complexity of the project, including all the new software components, the decision was made to focus on the main goal of the project, the acquisition. Therefore an electromagnetic tracking system was implemented. This requires that the amount of metal in proximity to the tracking system is kept to a minimum (requirement no. 21). This decision does not affect the functionality of blue-c and at a later date the electromagnetic system can easily be replaced by a vision based system.

## 2.2 PROJECTION SCREEN OPTIONS

To set up an immersive environment projection systems are normally used, which consist of multiple projectors. Head Mounted Displays (HMDs) can also be used with some limitations. For the visualization in blue-c it was decided that projection is more suitable than head mounted displays. The reasons against using HMDs for the blue-c project can be summarized as follows: A head mounted display covers a large part of the face, thereby making it unsuitable for conferencing. Shutter glasses are also big but compared to HMDs still acceptable for conferencing. Most HMDs are heavy and only offer a limited field of view (FOV). Furthermore, the latency between detecting a head movement and updating the image to the new head position is still noticeable, which is quite disturbing. With projection the visual feedback after a head rotation is immediate and other perspective corrections to head movements are much less disturbing and tolerate more latency. Due to these limitations, simulator sickness and nearsightedness only occur with extensive use of HMDs [25].

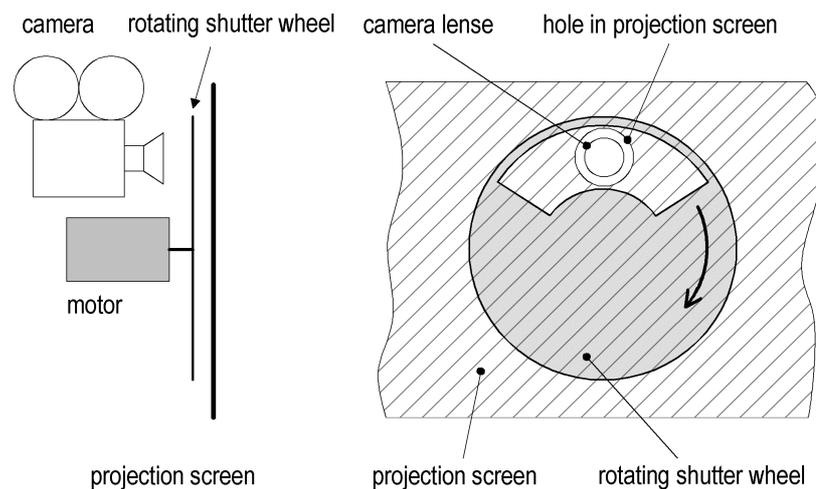
The question regarding the integration of cameras into an immersive projection environment without interfering with the projection arises. Different concepts are presented in the following sections.

### 2.2.1 Lipstick Cameras

An easy setup would be to integrate small lipstick cameras in the projection screen. The cameras could be mounted in small holes in the screen. For a back projection, this setup is not suitable because the cables from the cameras as well as the cameras themselves cause shadows in the projection. Even with a front projection, the lenses would be visible in the form of black dots. In addition, changing a camera position after installation would be quite complicated. Thus, this principle is suitable neither for front nor for back projection in blue-c.

### 2.2.2 Lipstick Cameras with Shutters

The proposed setup is based on the lipstick camera principle and is only suitable for front projections. The cameras could be placed directly behind a hole in the projection screen. Mechanical shutters close the holes during projection and open them during picture acquisition (Figure 2.1). Instead of creating black holes which would be visible during projection, this system only causes small disturbances in the projected image due to the white shutters in front of the camera lens. The whole shutter system has to be synchronized with the acquisition system. No investigations have been made on the amount of vibration and noise which would be generated by this mechanical system.

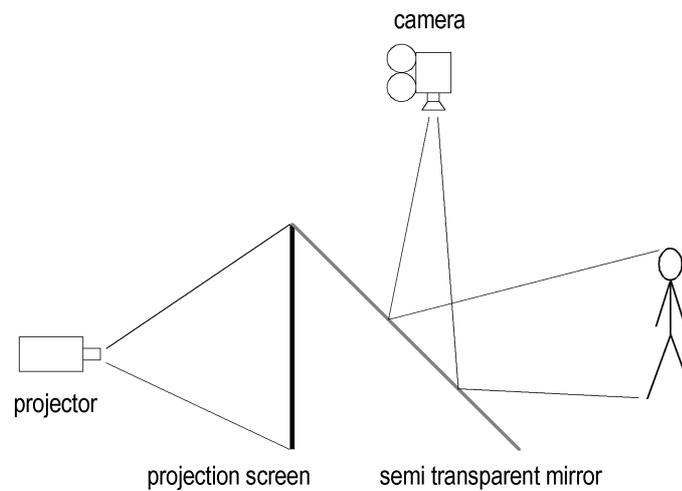


**Figure 2.1** Camera behind a rotating shutter wheel in combination with front projection

### 2.2.3 Semitransparent Mirror

A semitransparent mirror in front of the projection screen, as shown in Figure 2.2, would allow images to be acquired in the same way that a virtual camera would function behind the screen. As many cameras as desired could be integrated without disturbing the projection. Due to the distant position of the cameras, full coverage of a person inside the system would be assured. A disadvantage of this method is the loss of light from the projected image as well as from the acquired image. Furthermore, the construction is very large and the semitransparent mirror would have to have at least the size of the screen. If the mirror is mounted at an angle of  $45^\circ$  to the projection screen, its size would be 1.4 times that of the screen. A semitransparent mirror such as this one would be fragile and

very expensive. The upper region of the room would have to be completely dark, otherwise disturbing reflections would interfere with the projection.



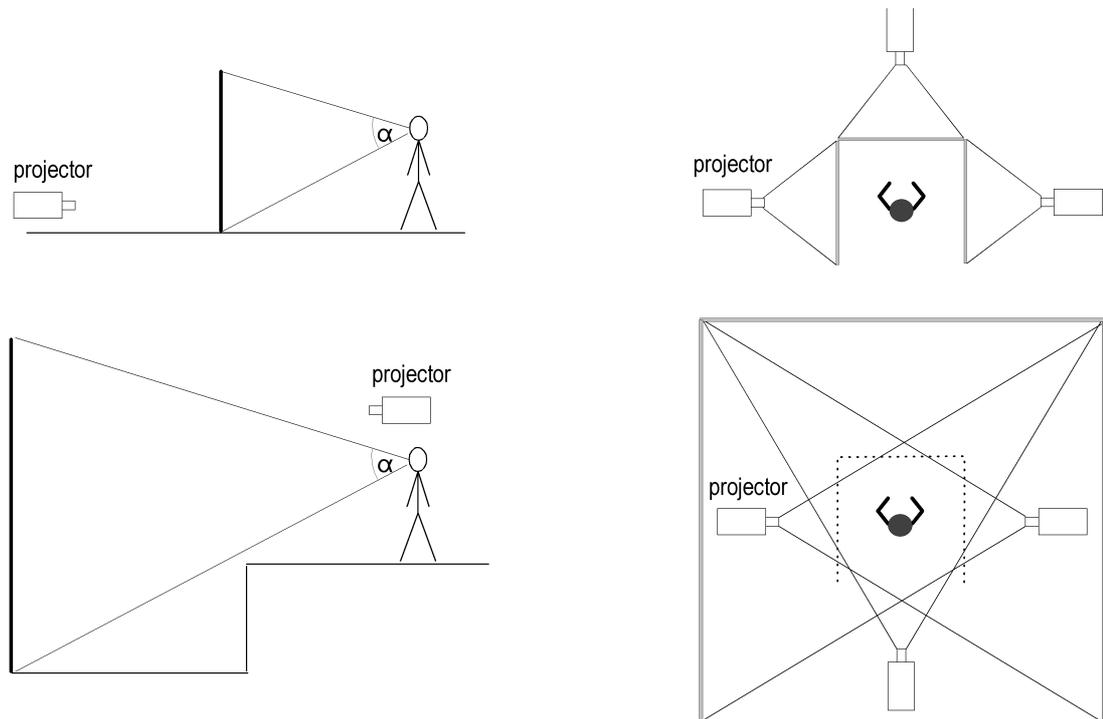
**Figure 2.2** Semitransparent mirror in front of the projection screen

#### 2.2.4 Immersive Front Projection

This approach is based on the fact that the field of view (FOV) is important for the degree of immersion. A back projection and a front projection could be set up in such a way that, from a defined position of the user's head, they will cover exactly the same FOV. In this case, the size of the screen would have to increase linearly with the distance of the observer to the screen. Therefore, a 2.1 m high and 2.8 m wide screen (projection ratio 3:4) at a distance of 1.5 m from the observer produces the same immersion that a 6.3 m high and 8.4 m wide screen would produce at a distance of 4.5 m. The observed brightness, on the other hand, decreases with increasing distance to the screen. The vertical viewing angle  $\alpha$  is in both cases  $65^\circ$  for a person with a 1.6 m eye height. A bigger screen at a longer distance has the advantage that the integrated cameras are much less disturbing for the user since their relative size is smaller compared to the screen size. Furthermore, if the user stays within the same confined area as he would with the smaller projection system, the user would always be within the full coverage range of the cameras.

Figure 2.3 shows a three-sided back projection (upper two images) and a three-sided front projection (lower two images). The vertical viewing angle  $\alpha$  as well as the viewing inclination angle is the same for both projections, as seen in the two images on the left.

On the top view of the front projection (lower right image) the working area, marked with dotted lines, is the same as for the back projection.



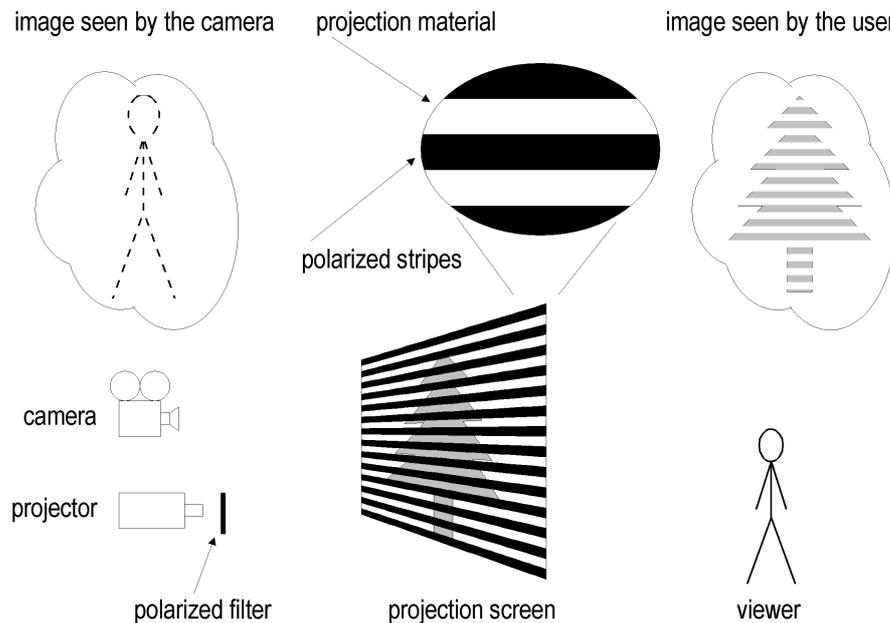
**Figure 2.3** Side and top view of a back projection (up) and a front projection (down)

Given that the height of the installation room is 4.5 m, the maximal screen size could be 4.5 m x 6 m. Under the assumption that the vertical viewing angle  $\alpha$  is  $65^\circ$ , the distance between the user and the screen would be 3.21 m. The user would have to stand on a platform, 1.8 m above the ground to have the same viewing inclination angle as he would have with the smaller screen. In a given working area of 3 m x 3 m it would be very difficult to setup a projection where the user or the base do not interfere with the projection beam. Furthermore, at a distance of 3.21 m from the screen, the camera lenses would still be very noticeable.

### 2.2.5 Polarized Stripes Projection Screen

The polarized stripes approach proposes the use of alternating polarizing structures in the projection screen for projection and acquisition. In Figure 2.4 for instance, horizontal stripes are used to divide the projection screen into projection and acquisition surfaces. The projection surfaces are coated with projection material (projection stripes). The acquisition surfaces are transparent stripes covered with a polarizer. Polarized light is used for the projection. The polarization orientation of the projected light is orthogonal to the polarization of the acquisition strips on the projection screen. The projection beam, therefore, does not pass through the acquisition stripes and only projects an image on the projection stripes. On the other hand, the cameras can look through the acquisition stripes at the user since the user is illuminated with non-polarized light. The cameras can be placed anywhere behind the projection screen out of the projection beam thereby producing good coverage of the user, which allows a large range of focus. A disadvantage to this approach is that only 50% of the range of projection, in terms of resolution and brightness, is used. Additional loss in brightness may occur, depending on the type of

projectors used and on how the polarization on the projector side is implemented. The same limitations also apply for the acquisition.



**Figure 2.4** Polarized stripe projection screen

Another way to combine opacity and translucency in one screen is to use a material, which has two preferred light paths. A holographic layer in a glass panel could be used for this property, as it has been done in some commercially available products. Light coming from a defined angle (e.g.  $36^\circ$ ) is redirected and forwarded perpendicularly on the other side of the screen, while light coming from other directions is not altered. Thus it is possible to simultaneously make a projection and to look through the holographic projection screen with the camera.

### 2.2.6 Shuttered Projection Screen

As in the approach of the “polarized stripe projection screen“ the cameras could be mounted anywhere behind the projection screen, out of the projection beam. A special projection screen has to be used, which can be switched from opaque to transparent and back. The idea is to use time multiplexing to combine the projection and acquisition [44]. 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 take images of the user inside the installation. The switchable projection screen has to be synchronized with the acquisition system. By switching between the transparent and opaque states quickly enough, no flickering will be observable and the cameras will not be visible to the user.

Switchable glass panels are commercially available and can be used as shuttered projection screens. They are based on phase dispersed liquid crystal (PDLC) technology and can be electrically switched from transparent to opaque. The maximum width of the panels which is available is 950 mm. For a projection room up to 2.85 m x 2.85 m three of these panels would have to be integrated per side. The gaps between the panels would be visible. The glass panel itself can cause reflections that are comparable to normal glass panels. Therefore, careful design of the installation and illumination is important.

## 2.3 EVALUATION OF THE DIFFERENT OPTIONS AND DECISION

The different concepts presented in the previous section were evaluated in order to decide which concept to use for blue-c. The front projection concept was not taken into consideration, since it is not suitable for the given room size as discussed in subchapter 2.2.4.

Since brightness and sharpness of the images, projected on the holographic screen, highly depend on the viewing angle, this material is also not suitable for SID systems and thus it was not taken into further account.

**Table 2.2** Evaluation

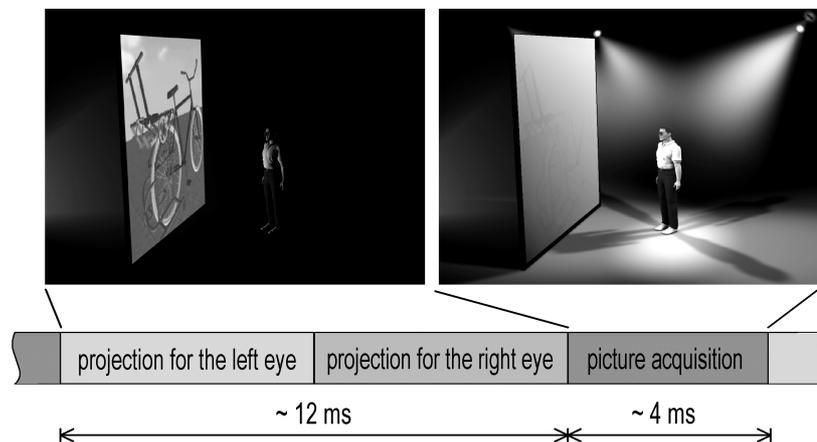
Criteria	Weighting (w)	Lipstick cameras		Lipstick cameras with shutter		Semi transparent mirror		Polarized stripes		Shuttered projection screen	
		value (v)	v*w	value (v)	v*w	value (v)	v*w	value (v)	v*w	value (v)	v*w
<i>projection</i>	0.3										
hot spot behavior	0.06	4	0.24	4	0.24	4	0.24	2	0.12	2	0.12
diffusion property	0.06	4	0.24	4	0.24	3	0.18	3	0.18	3	0.18
reflection property	0.06	4	0.24	4	0.24	1	0.06	2	0.12	1	0.06
disturbances (points, lines)	0.06	1	0.06	2	0.12	3	0.18	1	0.06	2	0.12
shadows and interferences	0.06	1	0.06	1	0.06	3	0.18	4	0.24	4	0.24
<i>acquisition</i>	0.4										
distance of camera to object	0.04	1	0.04	1	0.04	4	0.16	4	0.16	4	0.16
coverage by cameras	0.08	1	0.08	1	0.08	4	0.32	4	0.32	4	0.32
acquired image quality	0.12	3	0.36	3	0.36	2	0.24	1	0.12	1	0.12
flexibility of camera positions	0.16	1	0.16	1	0.16	3	0.48	4	0.64	4	0.64
<i>construction</i>	0.3										
construction complexity	0.06	4	0.24	3	0.18	2	0.12	1	0.06	3	0.18
technical feasibility	0.06	4	0.24	2	0.12	1	0.06	1	0.06	2	0.12
implementation time	0.09	4	0.36	3	0.27	2	0.18	1	0.09	2	0.18
costs	0.09	4	0.36	3	0.27	1	0.09	2	0.18	3	0.27
TOTAL			2.68		2.38		2.49		2.35		2.71

Different criteria concerning the projection, acquisition and construction were used for the evaluation of the remaining concepts. Each solution was rated with a value between 1 (poor) and 4 (very good) for each of the criteria.

The active projection screen offers the best compromise between projection, picture acquisition and construction. The projection quality is good, as it is only disturbed by vertical stripes between the different glass panels. In regards to the acquisition, the main advantage is the placement of the cameras. They can be placed anywhere behind the screens, as long as they do not interfere with the projection beam. Therefore, they can cover the whole person independently of the person's position in blue-c. The concept with the switchable glass also offers a good level of flexibility which was necessary for an experimental setup when the project was first initiated, since the camera position can be changed as often as needed. This, of course, would not be possible if the cameras would be mounted behind holes in the projection screens. Preliminary tests showed that the shuttered projection screens can be switched at frequencies of 60 Hz with an acceptable delay in response time.

## 2.4 THE THREE PHASES

With the use of actively shuttered projection screens, the projection and acquisition have to take place at different moments. This time multiplexing between projection and acquisition has two or three different phases, depending on the projection. For a normal projection two time phases are necessary, one for projection and one for acquisition. In combination with an active stereo projection the number of phases are three; one for the left eye projection, one for the right eye projection and one for the image acquisition [48]. This sequence has to be repeated with a frequency, which is high enough to avoid noticeable flickering.

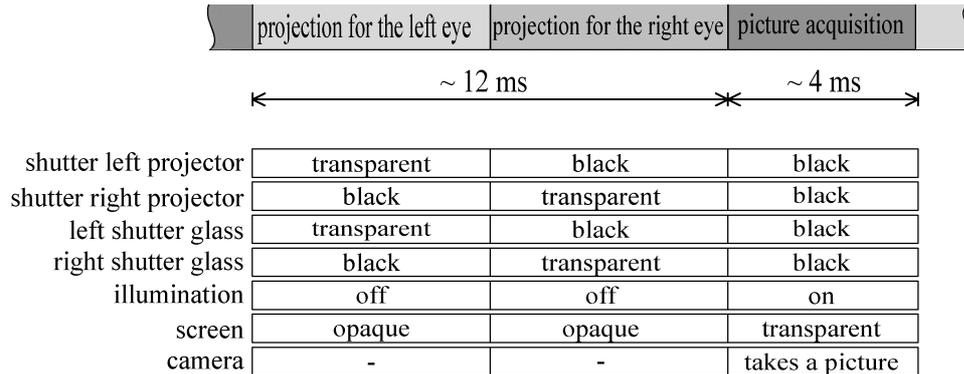


**Figure 2.5** The three phases

An important question arose regarding the method for illuminating the user without disturbing the user and without altering the projection quality and thus the degree of immersion. The illumination has to be in the visible light spectrum since color cameras are used. The idea is to make use of the three phases and to have a flash illumination which is only activated during picture acquisition. To protect the user from the light shutter glasses are worn, which are synchronized with the illumination [45], [47]. These shutter glasses are also needed for the active stereoscopic projection. Figure 2.5 illustrates such a

projection sequence, which is followed by an acquisition sequence. The frequency of the flash illumination as well as of all other visible devices has to be kept high enough (e.g. 62.5 Hz) so as not to disturb the user with annoying flickering.

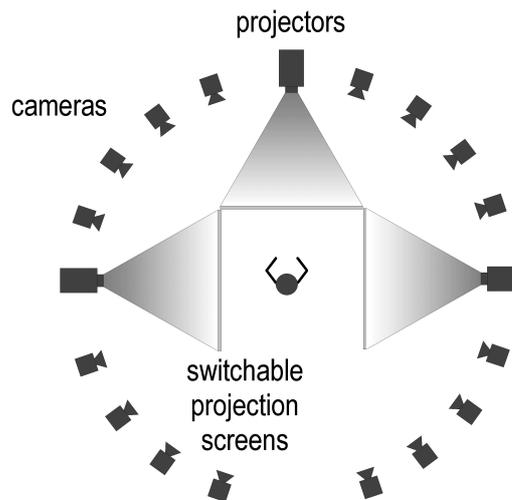
The components which needed to be synchronized are listed on the left side of Figure 2.6. The projectors have to be turned off during acquisition to avoid projecting directly onto the user, as well as causing reflections on the active projection screens during acquisition. For this reason, additional shutters are mounted in front of the projectors, which remain closed during acquisition. These shutters can also be used to generate a stereo projection as described in chapter 3.



**Figure 2.6** Timing of the three phases

## 2.5 SETUP

The active projection screens allow the cameras to be arranged around the projection room. The layout of blue-c is a three-sided projection room with a quadratic ground view (Figure 2.7). This quadratic layout, as it has been used for the first time in the CAVE™ [6], allows standard projection hardware to be used. Edge blending is not required because the different projections are on different screens.



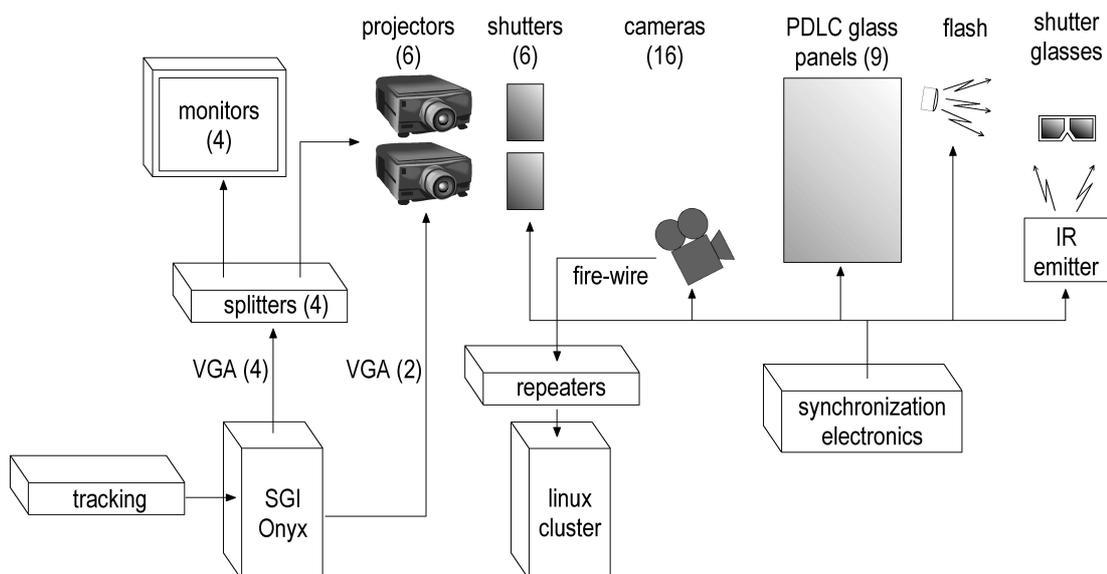
**Figure 2.7** blue-c layout

Figure 2.8 shows an overview of all components of blue-c, including the connection scheme. Two projectors in combination with two shutters are used per side to generate a stereoscopic projection [40]. The six projectors of the three-sided projection room are connected to a SGI Onyx 3200. The control room of blue-c is equipped with four SGI monitors, which share the graphic pipes with four of the six projectors. When an application is running in blue-c, the operator can see both channels of the blue-c's middle projection screen as well as the two left eye channels of the left and right screens. When an application is not running in blue-c, the monitors can be used at full resolution of 1920 x 1080. Four two-way splitters are connected to the corresponding outputs of the SGI. The splitters have a bandwidth of 500 MHz (3dB bandwidth). The signal going to the projectors is a XGA (1024 x 768) 60 Hz signal [40]. The projection system is discussed in detail in Chapter 3.

The sixteen cameras of blue-c are connected with fire-wire cables to a Linux cluster. The Linux cluster consists of seventeen nodes. Each of the cameras is connected to a single-processor node which preprocesses the incoming images. The sixteen nodes are connected over a proprietary 100 Mbit Ethernet link to a dual-processor node. The preprocessed images are transferred to this dual-processor machine, which generates a 3D model of the acquired person.

A total of nine PDLC glass panels are used for the three active projection screens. They are switched to transparent in order for the cameras to acquire an image and to opaque for the projection. The active projection screens are the subject of Chapter 4.

A flash illumination consisting of LEDs is used to illuminate the inside of blue-c to allow the cameras to take decent images. This illumination is switched on during image acquisition and switched off for projection. The user wears modified shutter glasses, which allow him to see the stereo projection and which protect the user's eyes from the illumination caused by the flash. Chapter 5 explains the details of the flash illumination and the modified shutter glasses.



**Figure 2.8** Components overview

The PDLC glass panels, the shutters in front of the projectors, the flash illumination, the cameras as well as the IR-emitter for the shutter glasses are synchronized by custom-made synchronization electronics. As seen from Figure 2.8, there is no electrical

connection between the SGI Onyx (together with the projectors) and the rest of the components. This allows the image acquisition to run independently from the rendering system, thereby achieving more flexibility. The synchronization electronics are discussed in detail in Chapter 6. The exact trigger timings are explained in Chapter 8.

## STEREO PROJECTION

Since the beginning of photography, people have tried to capture the third dimension with the help of stereoscopy. Two different images, corresponding to the view of each eye, were captured and presented to the viewer with a special binocular mechanism. Today, with the advances in computer graphics, the stereoscopic visualization of computer data has given a considerable boost to stereo projection and display systems. Most of the systems use projections in combination with special eyewear to generate the 3D images. Also some approaches were made to enable glasses-free stereo experiences with auto stereoscopic displays and projections. One approach is to write the right image into the even numbered columns of a flat panel display (FPD) and the left image into the odd numbered columns, respectively. The left and the right images are correctly presented to the right and the left eye, using a prism mask in front of the FPD [9]. A head tracking mechanism is necessary for detecting the position of the user's head and moving the mask accordingly. This kind of display can reproduce a realistically accurate stereo projection only if the user's head is within a defined distance range from the display. Alternatively to the prism mask a lenticular mask can be used [9]. This technology, consisting of a moving mask in front of the screen, is only applicable for medium and small displays. A projection in combination with a directional reflection screen is an alternative to the small displays. Two projectors are positioned in such a way, that the two projections are directly reflected into the corresponding user's eye [11]. This method only works for one single head position. The viewing area can be enlarged by using more projectors. With an increasing number of projectors, the computer power also has to be increased. The glass-free multi-viewer stereoscopic viewing experience is, therefore, expensive because of added computational power and a large number of projectors.

Stereo projections where the user has to wear special eyewear, are the most common method. These stereoscopic systems can be scaled and combined to multi-projection systems without any problems and are based on commonly used projection hardware. The image for the left and the right eye are projected on the same screen and are then separated by the eyewear to give the correct image to each eye. This works independent of the viewer's position in relation to the projection screen. Stereo projection systems using special eyewear will be discussed in detail in section 3.2.

### 3.1 HUMAN ANATOMY

The eye is one of the most important sensory organs for the perception of the environment. It can acquire an incredible amount of information. Only in situations when the visual system reaches its limits, do the other sensory organs start to play a dominant role. The same applies for virtual reality (VR), where most information is transmitted visually. Therefore, in order to set up an immersive projection system, it is important to understand how the human visual perception functions. Of particular interest is depth perception, from which the distance of the eye to an object can be determined.

#### 3.1.1 Viewing Angle

The viewing angle is determined by the physical construction of the eye and by its position in the face. When the eye is directed forward and kept stationary, the viewing angle of a healthy eye is limited by the nose, the brow as well as other parts of the face. The four viewing angles as measured by W. Charman [16] are listed in Table 3.1. The angles have been measured in relation to the visual axes with the eyes directed forward.

**Table 3.1** Viewing angles

Nasal	Temporal	Superior	Inferior
60°	100°	60°	70°

With a straight ahead view, the combined horizontal viewing angle of the two eyes is  $\pm 100^\circ$ , with an overlapping coverage of  $120^\circ$ . Despite the large viewing field, the human eye only has sharp vision in a relatively narrow area. The eye has, therefore, to be directed towards the detail of interest. Theoretically, the eye can scan a field extending  $\pm 45^\circ$ . In practice, only about  $\pm 20^\circ$  are used and bigger movements are assisted by head rotation [51].

When building an immersive VR system, the large field of view of the human visual system has to be taken into consideration. Projection systems with multiple surrounding screens, which cover a large field of view and also allow head movements are therefore desirable.

#### 3.1.2 Temporal Resolution

The human eye is most sensitive to flickering at its periphery. Flickering frequencies around 20 Hz are the most disturbing. For frequencies above 60 Hz, no disturbances are reported and the eye adapts to the average brightness [16].

A frequency of 20 Hz is the limit concerning the temporal resolution of single images. Above this frequency the human eye can no longer distinguish between different images. Nevertheless flickering may still be visible. Some TV sets and most professional movie projection systems take advantage of this fact by projecting each image twice. This eliminates flickering while still maintaining the original frame rate.

The pupil itself is slower compared to the temporal resolution and can respond to changes in light level at frequencies up to about 4 Hz [16].

For a VR system it is therefore important that all visible components are triggered with frequencies above the flickering frequency. This also applies to the components which are only peripherally and weakly visible. In blue-c the visible triggered components are the

shutter glasses, the stereo projection, the active illumination and the active projection screens.

### 3.1.3 Depth Perception

Many different factors contribute to depth perception. Some perceptions of depth can be experienced with one eye while others rely on binocular vision. The experiences which the human has had will also play an important role in depth perception. For example, it is much easier to estimate the distance of a known object than of an unknown object. In the following section an overview of relevant factors for depth perception is given [23], [17].

**Motion Parallax.** When in motion, closer objects “move“ more than distant ones.

**Occlusion.** Distant objects are partially obscured by closer ones.

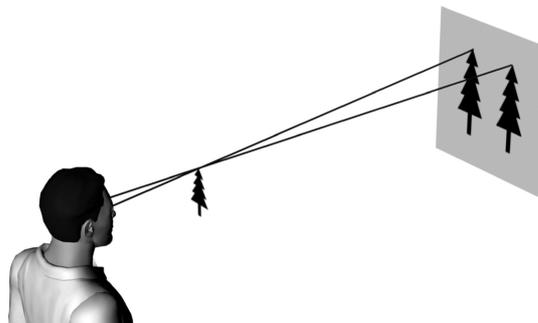
**Perspective.** The classic railway tracks, which appear to get closer together when they are further away.

**Binocular disparity.** Each eye sees a slightly different view of the world and the brain can determine distance based on the differences.

**Accommodation.** The distance at which the eye is focused.

**Convergence.** The eyes rotate around the body’s vertical axis to point the eyes at close objects.

A normal mono projection can make use of parallax, occlusion and perspective. In addition, a stereo projection uses the binocular disparity and convergence. Figure 3.1 illustrates the principle of a stereo projection. The left and the right eye see two different images of a tree, thereby giving the illusion that the tree is located in front of the projection screen. The technical realization is discussed in section 3.2.



**Figure 3.1** Stereo projection

Unfortunately there is no projection technique which can appropriately stimulate accommodation. With a mono or stereo projection, accommodation always has to be done to the screen surface. Furthermore in the real world, objects at depths that differ from that of the fixated target are blurred, whereas in a virtual environment they are (unnaturally) in focus. This decoupling between convergence and accommodation may be a cause of eyestrain. A remedy to this problem is to slightly blur the projected image. With a non-stereoscopic display a higher resolution is preferred since it produces a better stimulus for accommodation. With stereoscopic displays, improvements in resolutions increase the conflict between accommodation and the convergence system [24].

## 3.2 STEREO PROJECTION SYSTEMS

Stereo projection makes use of the ability of humans to estimate the distance of an object by binocular disparity and convergence. Therefore, two different images have to be presented to the person's left and right eye. In order to do so, different types of multiplexing are used. The projection system consists of a multiplexing system in the form of one or two projectors and a de-multiplexing system, normally in the form of glasses worn by the user. It is important that the transmission medium, such as the projection screen, maintains the multiplex coding.

### 3.2.1 Comparison and Discussion

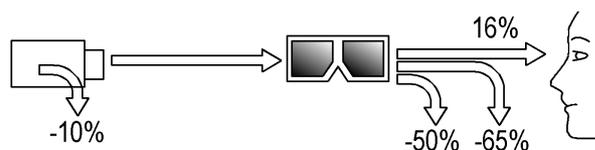
A stereo projection system can be qualified by different criteria. One of them is the light loss of the stereo projection system compared to an equivalent normal projection system. Another very important factor for a projected image is the so-called contrast ratio, which compares the "wanted" amount of light coming from the projection with the "unwanted" ambient light. This ratio should be as high as possible in order to reach a good level of projection quality. If the projection screen is additionally illuminated with ambient light, the projected image fades or becomes completely invisible. Thus it is important to also know the attenuation of the system for ambient light.

In the following section, the most common stereo projection systems are presented. The percentages are calculated in relation to the total light output of the projection system and indicate the total light perceived by one eye.

**Active stereo projection.** Active stereo projection uses time multiplexing to encode the two views [23]. The images for the left and the right eyes are projected sequentially with the same projector. Shutter glasses, which are synchronized with the projection system, assure that the images for the left and the right eye are separated correctly [20]. Only CRT and DLP projectors are fast enough to switch between the two images for the left and right eye.

As the left and right eye images are sequentially projected with one projector, the duty cycle per eye is 50%. However, an extra blanking of about 10% between the left and right image is required to ensure appropriate separation of the two stereo channels. Since both channels are projected with the same projector, the light loss in the projector itself only consists of the 10% blanking time. Then the unpolarized light has to pass through the shutter glasses, which separates the two channels. The separation process itself blocks 50% of the projection and only lets the images for the corresponding eye pass through. The LC-shutters, with their polarizers, cause an additional loss of approximately 65% [19]. Therefore, the total efficiency of an active stereo projection system per eye is

$$I = 90\% \cdot 50\% \cdot 35\% = 16\% \quad (3.1)$$



**Figure 3.2** Active stereo projection (single CRT or DLP projector)

The ambient light reflected or passing through the projection screen is unpolarized. When the light passes through the shutter glasses about 50% is lost corresponding to the

black period of each eye's shutter glass panel. From the remaining light, another 65% is lost as it passes through the polarizers of the shutter glasses. Therefore, only about 17.5% of the ambient light reaches the user. The contrast ratio is

$$C = \frac{16\%}{17.5\%} = 0.91. \quad (3.2)$$

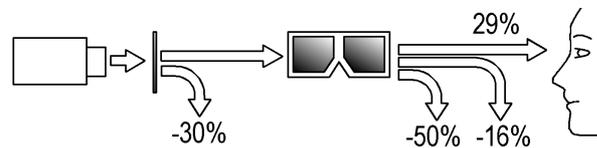
**LCD passive stereo projection.** Passive stereo projection consists of two projectors per screen. One projects the images for the left eye while the other simultaneously projects the images for the right eye. The two projectors are equipped with external polarizers, in which the axis is oriented orthogonally between each one. The user has to wear polarized glasses with the polarization axes oriented accordingly to the axes of the polarizers, which are located in front of the projectors. The polarized glasses are worn in order to separate the two projection channels. The projection screen which is used has to maintain the polarization.

LCD projectors emit polarized light, which in the case of a three chip projector, is normally aligned in two different axes. This light can be aligned to a single polarization axis by placing an external polarizer in front of the projector lens. To avoid color distortion it is important that the polarization axes of the external polarizer is exactly aligned with the bisecting line between the two original polarization axes. Fortunately in most LCD projectors the two polarization axes are more or less orthogonal to each other, thereby allowing an orthogonal orientation of the two external filters while keeping the same light throughput.

The cumulated light of the two projectors is set as the 100% reference for the following evaluation. The light of the projection passing through the external polarizers is attenuated by 30% [34]. After passing through the projection screen, this polarized light has to then pass through the polarized glasses. For each eye, one of the two projectors is almost completely blocked since the polarization axes are orthogonal, which results in a 50% loss of light. The light produced by the projector which passes through has the same polarization axes as the polarized filter in the glasses, which therefore only loses about 16% of intensity due to imperfections in the filters [22]. In summary, from the total light of the projectors only

$$I = 70\% \cdot 50\% \cdot 84\% = 29\% \quad (3.3)$$

reaches each of the eyes.



**Figure 3.3** Passive stereo projection (two LCD projectors)

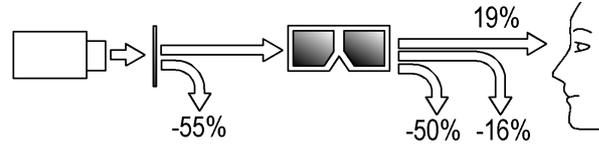
About 42% of the unpolarized ambient light passes through the polarized glasses. The contrast ratio is therefore

$$C = \frac{29\%}{42\%} = 0.69. \quad (3.4)$$

**CRT and DLP passive stereo projection.** This stereo projection method is basically the same as the LCD passive stereo projection. The primary difference is that the CRT

and DLP projectors project unpolarized light. In this case, the loss caused by the polarizer at the output of the projector is approximately 55%. Therefore, the total efficiency of the two projectors system per eye is

$$I = 45\% \cdot 50\% \cdot 84\% = 19\%. \quad (3.5)$$



**Figure 3.4** Passive stereo projection (two CRT or DLP projectors)

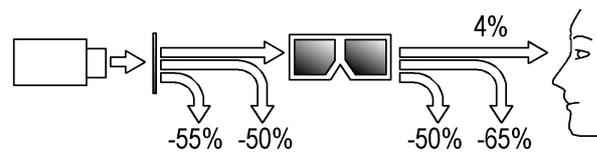
Again about 42% of the ambient light passes through the polarized glasses. The contrast ratio in this case is

$$C = \frac{19\%}{42\%} = 0.45. \quad (3.6)$$

**Active LCD stereo projection.** Active LCD stereo projection systems are not commercially available. The proposed system has been developed at the ZPE institute for the blue-c project. Similar to the LCD passive stereo projection, two projectors are used to generate a stereo projection. One of them is always projecting the image for the left eye while the other is projecting the image for the right eye. External LC shutters in front of the projectors alternately open and close the projector beams. Thereby generating an active stereo projection, which can be seen with the help of shutter glasses. Since most LCD projectors project almost continuously without interruption between image updates [37], there is no need to synchronize the external shutters with the refresh rate of the projector. This feature allows complete freedom when choosing the stereo frequency and projection duration per eye.

To determine the light loss of this system, it is assumed that both projectors are projecting continuously and that the external shutter allows each image to be projected with a 45% duty cycle. This already includes an extra blanking between the left and right images to guarantee a good separation of the two stereo channels. The light coming out of the LCD projectors is already polarized. This light has to pass through the LC shutters which consist of two glass panels with linear polarizers and liquid crystals in between. The LC shutters have to be oriented according to their first polarizers so that all three colors of the projectors pass through equally. The light loss caused by the LC shutter in the transparent state is about 50%. The light of both projectors reaches the projection wall, where it is depolarized by the used PDLC glass panels. After the projection wall, the light has to pass through the shutter glasses. Each of the two shutters in the glasses block one projection completely and let the other pass through with an efficiency of about 35%. Therefore, the total efficiency of this system is

$$I = 45\% \cdot 50\% \cdot 50\% \cdot 35\% = 4\% \quad (3.7)$$



**Figure 3.5** Active stereo projection with external LC shutters (two LCD projectors)

About 50% of the ambient light is lost during the black period of each eye's shutter glass panel. From the remaining light, another 65% is lost when passing through the shutter glasses in the transparent state. Therefore, 17.5% of the ambient light reaches the user. The contrast ratio in this case is

$$C = \frac{4}{17.5} = 0.23. \quad (3.8)$$

As exemplified by the comparison of the different stereo projection systems, the passive stereo projection has the highest level of efficiency. On the other hand, the contrast ratio is best when using a DLP or CRT active stereo projection. The comparison does not take into account the different light outputs of the projectors themselves and the human light perception, which is logarithmic.

Passive stereo projection systems offer a high light output for a competitive price. Inexpensive polarized eyewear can be used to experience the stereo projection. The drawback is that passive systems need special projection screens, which maintain polarization. Furthermore, the systems are susceptible to head inclination since the polarizers of the stereo glasses have to be aligned with the polarizers in front of the projectors.

Active stereo projection systems offer a good channel separation between the two projected images. The LCD active projection systems have a higher light loss compared to other active systems however they are also less expensive. In the year 2000, when the projection system for blue-c was selected, active DLP projectors were just emerging and they were five to ten times more expensive than the proposed active LCD system. On the other hand, the active CRT projectors that are normally used have a lower light output compared to LCD and DLP projectors. Moreover, they are double the cost of an active LCD stereo projection system. In regards to these aspects, the active stereo projection system was a valid alternative to the other active projection systems. Furthermore, the external shutters offered considerable advantages for the blue-c project, as discussed in the next section.

### 3.2.2 Decision

blue-c is a three-sided immersive projection room. The projection has to work in combination with the image acquisition system and has to be compatible with the PDLC glass panels. The requirements for the blue-c projection system are:

- ◆ Compatibility with PDLC projection screens (PDLC do not retain polarization)
- ◆ Blanking with adjustable duration and frequency for image acquisition.
- ◆ Projection intensity suited for a three-sided projection room.

Under these conditions the LCD active stereo projection system is the most suitable system for blue-c. The reasons can be summarized as follows:

- ◆ Only active stereo projection systems are compatible with the PDLC glass panels, which are used as projection screens in blue-c, because PDLC panels do not keep the polarization.
- ◆ The external shutters give a high level of flexibility concerning the timings for the stereo projection, including the blanking required during image acquisition.
- ◆ No synchronization is needed between the projectors and the shutters.
- ◆ The system has enough light output for a multisided immersive projection room. Too much projection light would light up the adjacent projection screens and thus reduce the contrast.
- ◆ The price is lower than comparable active stereo CRT or DLP solutions.

The technical realization of the active LCD stereo projection system is discussed in the next section.

### 3.3 ACTIVE LCD STEREO PROJECTION

Active LCD stereo projection systems are not commercially available. The system has been developed especially for blue-c because it offers some important advantages in combination with the simultaneous image acquisition of the blue-c project.



**Figure 3.6** Active LCD stereo projection system

The active LCD stereo projection system of blue-c uses two Sanyo XF12 three chip LCD projectors per side. They have a XGA (3x1024x768 pixels) resolution and 3500 ANSI lumen output. The projectors are equipped with a 1.2:1 lens for a short projection distance. Each system consists of a separate rack, where two projectors are mounted one upon the other. The alignment of the projectors can be adjusted to provide a congruent projection. Ferroelectric (FE) liquid crystal shutters with a size of 140 mm x 140 mm are

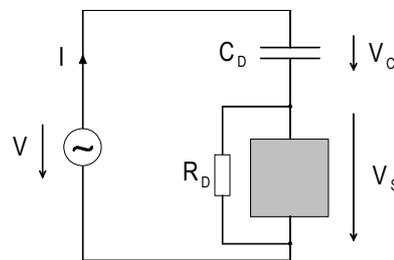
mounted in front of each projector. The cost of the active LCD stereo projection system, consisting of two projectors, two shutters and one rack, is approximately € 33,000.-. Figure 3.6 shows one of the three projection systems installed in blue-c. The shutters in front of the projectors are rotated in order to be correctly aligned between the polarized light from the projectors and the polarizers of the shutter.

### 3.3.1 Ferroelectric Shutters

The shutters in front of the projectors have to be switched on and off with a frequency of approximately 60 Hz.

Twisted Nematic (TN) liquid crystal shutters, as used in shutter glasses, can have a contrast ratio of 1000:1 or better [35]. They switch in about 2.5 ms from black to transparent and reversely they switch from transparent to black in less than 1 ms [19], [18] [36]. Ferroelectric (FE) liquid crystal shutters have approximately the same contrast ratio as TN shutters, yet they have much faster switching times. For the blue-c projection system, custom-made FE shutters from CRL Opto are used. These shutters are 140 mm x 140 mm and have a contrast ratio of approximately 750:1. The switching time from 10% to 90% transparency and from 90% to 10% transparency is below 100  $\mu$ s as measured by CRL Opto.

A TN shutter switches to black if a voltage is applied and switches to transparent if the voltage is removed. In comparison, a FE shutter switches to black if a voltage of one polarity is applied and switches to transparent if a voltage of the opposite polarity is applied. It is important, that the shutter is not subject to any DC voltage, otherwise it would be damaged. The DC decoupling is achieved by connecting a capacitor  $C_D$  of 1  $\mu$ F in series and a resistor  $R_D$  of 2.2 k $\Omega$  in parallel to the shutter (Figure 3.7).



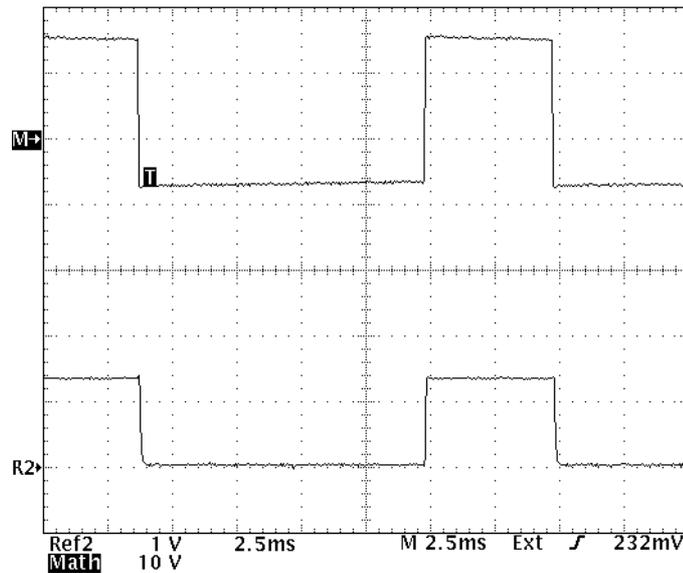
**Figure 3.7** DC decoupling of shutter

The shutter with the decoupling circuit is connected to the control electronics. The control electronics switches between +11.5 V to open and -11.5 V to close the shutter. In the measurements show in Figure 3.8, the on time is 5 ms and the off time is 11 ms. Following a few cycles, the DC component of the voltage is absorbed by the capacitor. The voltage of the capacitor is then

$$V_C = \frac{11.5V \cdot 5ms - 11.5V \cdot 11ms}{16ms} = -4.3125V. \quad (3.9)$$

As a result, the voltage  $V_S$  measured on the shutter itself changes between +15.8125 V and -7.1875 V. The upper measurement in Figure 3.8 displays 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. The response is very fast and guarantees an excellent separation of the two stereo channels.



**Figure 3.8** Ferroelectric LC shutter (driving voltage, optical response)

### 3.3.2 Calibration

Since flat screens are used, no pre-deformation of the image is needed and the calibration effort is reduced to an electronic and a mechanical calibration. Due to the rectangular shape of blue-c, edge-blending between the three different screens is not needed.

**Electronic calibration.** The calibration of the projectors mainly concerns the phase and sync settings. This implies that the SGI's graphic pipes are set to the native resolution and frequency of the projectors. The phase and sync values of the projectors are tuned so that each pixel of the SGI graphic pipe is mapped to the corresponding pixel of the projector. This calibration is best achieved with an appropriate static test image. The test image should be composed of a one pixel wide frame, surrounding the image and a pixel wide alternating black and white pattern in the rest of the image. An experienced person needs approximately 20 min. to calibrate one projector. If a splitter is set in the path, the calibration has to be redone.

**Mechanical calibration.** The electronic calibration of all six projectors is followed by the mechanical alignment of the projectors. This mechanical alignment is needed for an exact stereoscopic projection as well as for a sharp monoscopic image. For this task, a test pattern with a large mesh can be used. The mesh should consist of lines which are one pixel wide.

Each projector rack of blue-c has one projector mounted with 4 degrees of freedom and one with 6 degrees of freedom. The process of mechanical calibration in blue-c is started with the center projector, 4 degrees of freedom. To adjust the missing two degrees of freedom, the whole projector stack can be moved around. After having aligned the first center projector, the image of the second projector has to be adjusted to exactly fit to the first one. The same procedure has to be repeated with the left and the right projector stack. The only difference is that they also have to be in line with the middle unit. A satisfactory mechanical calibration takes about 4 hours to complete.

## ACTIVE PROJECTION SCREEN

This chapter describes the function and the physical properties of the active projection screens, which are a core element of blue-c.

The projection screens in blue-c have to be switchable between two states, an opaque state for projection and a transparent state for image acquisition [44]. The process of switching from one state to the other has to be fast and controllable. Chromogenic material can change the optical property on demand and some of these materials can even make this change within a fraction of second. This property is used, for example, in architectural design where facades of buildings are constructed with active glass panels. These panels allow the thermal flow of buildings to be regulated, thereby helping to save energy. There is a variety of active materials available which can change their optical properties. In most cases, glass panels are used as the substrate for the active material. A wide variety of active materials with different optical characteristics exist. Some of them change from a clear state to a dark state but do not scatter light. Others change from a transparent state to an opaque state. The latter property is of interest for building a switchable projection wall. The active materials can be controlled thermally (thermochromic material), electrically or optically with UV light (photochromic material). For example, the photochromic materials used in sun glasses, which are capable of changing their property in correlation to the intensity of the sun. The adaptation in this case takes approximately three minutes. A wide variety of switchable materials are listed in [30] and comprise electrochromics (EC), suspended particle devices (SPD), phase dispersed liquid crystals (PDLC), cholesteric liquid crystals (ChLC), thermotropic (TT), thermochromic (TC), photochromic (PC) and gaschromic (GC).

For producing an active projection screen, the panels with phase dispersed liquid crystal (PDLC) layers are the most suitable type of panels. They can be controlled electrically, can be switched in a few milliseconds or less and change from a transparent to an opaque state.

Several different glass manufacturers produce switchable glass panels that are available with an integrated PDLC layer.



**Figure 4.1** Three PDLC glass panels, middle panel switched transparent

## 4.1 PHYSICS

The most common type of liquid crystals (LC) that are used for displays are the twisted nematic liquid crystals. The mechanism used for optical switching is the change of the orientation or twist of liquid crystal molecules interspersed between two conductive electrodes with an applied electric field [31].

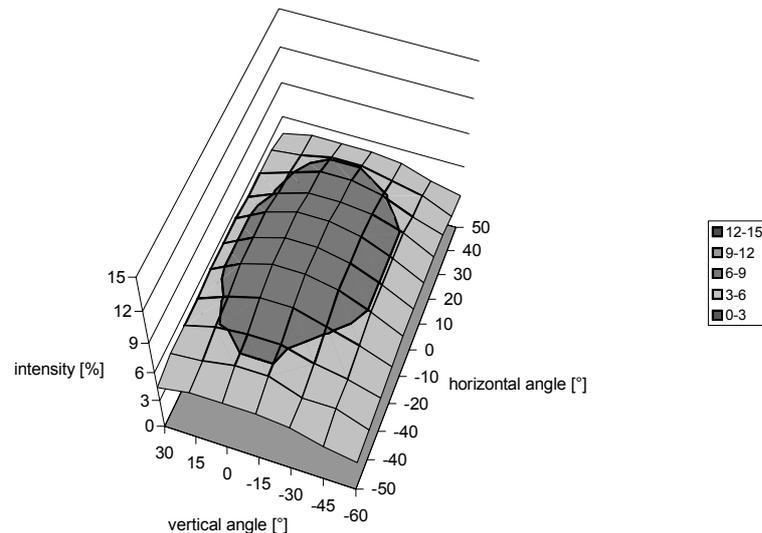
One fairly unusual version of a liquid crystal system is produced by making an emulsion of a polymer and liquid crystal in order to form a film. This emulsion is called phase dispersed liquid crystal (PDLC) and consists of liquid crystal droplets ( $5\ \mu\text{m}$ ) which are encapsulated within a diffraction index matched polymer matrix ( $22\ \mu\text{m}$ ) [30]. The polymer emulsion is fabricated between two sheets of transparent conductor-coated polyester or glass, which serve as electrodes. The switching effect of this device spans the entire solar spectrum, up to the absorption frequency edge of glass. The liquid crystal droplets are randomly oriented in the off state, when no voltage is applied. This variation in liquid crystal alignment throughout the film provides the scattering properties seen in many PDLC devices. When a voltage is applied to the electrodes, an electrical field is generated which forces the liquid crystals to align in the direction of the field thus perpendicular to the glass panel surface. Like other liquid crystal devices, the reorientation field is determined by the balance of elastic forces (which resist orientation) and electric forces (which induce orientation) [32]. The rise time for PDLC materials are typically around one millisecond, while decay times are often a few milliseconds. The decay time is mostly determined by the physical property of the PDLC film itself and can scarcely be influenced by the electrical control. PDLC devices typically operate at around 50 V to 100 V ac and have a power consumption of less than  $5\ \text{W}/\text{m}^2$ .

## 4.2 PROJECTION QUALITY

The projection quality of a back projection screen is mainly influenced by the hot spot, the diffusion depending on the viewing angle as well as the reflective properties. The diffusion describes how a projected image is seen under different viewing angles. In an immersive projection room such as blue-c, where people look at different screens, this property is very important. Since the users can be very close to the projection screens, the viewing angle can vary widely. In addition, the users can look at different screens, placed orthogonal to each other, which dramatically increases the viewing angle. Another important characteristic of a projection is the hot spot. The hot spot is the brightest point of a projection. This is correlated to the projector position and is basically projection light which passes with little diffusion straight through the projection screen towards the user. The hot spot and diffusion of a projection screen are related to each other. The hot spot is measured as a high projection intensity gain under a confined viewing angle. An average high intensity value is also desirable but less important than a homogeneous diffusion. This is especially the case with a surrounding projection environment, where too much projection luminosity on one screen would fade out the projection on the adjacent screen.

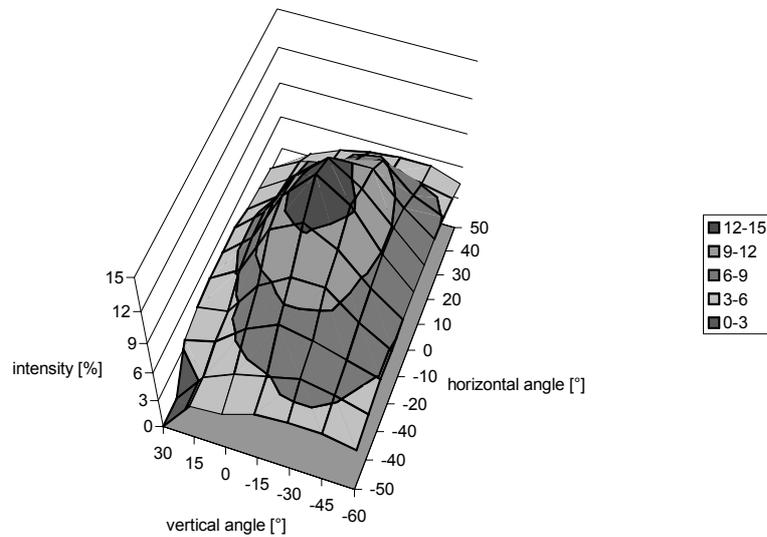
To analyze the projection properties of active projection screens, the relative projection intensity under different viewing angles has been measured. The setup consisted of a back projection, mounted at a distance of 2.5 m from the screen. The projector was projecting 15° off-axis, below the measurement point. A 100% white image was projected. In the measurements, the projection intensity has been scaled. The highest projection intensity of all measurements corresponds to 100% and the lowest corresponds to 0%. For a good quality projection it is important that this intensity is distributed homogeneously.

Two reference projection screens have also been measured. The back projection screen C, which is utilized for immersive projection rooms, shows a very homogenous distribution and a good average level of intensity (Figure 4.2).



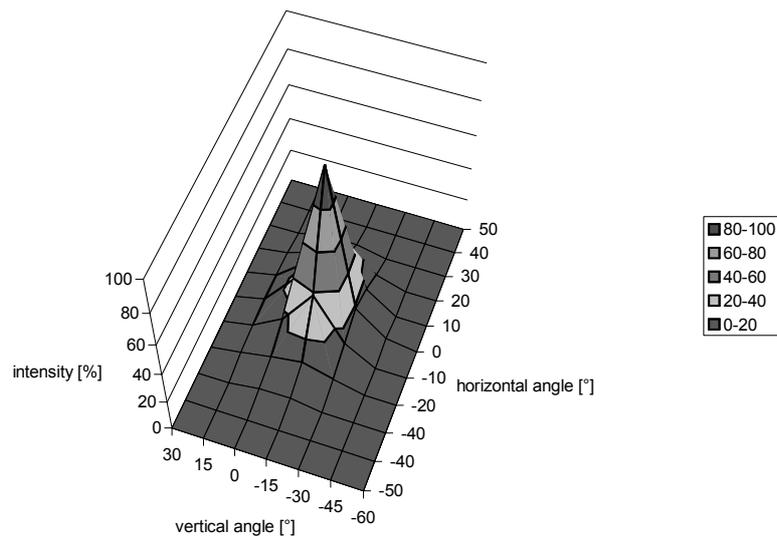
**Figure 4.2** Projection screen C

The projection screen D, a 2mm thick back projection screen, has a more accentuated hot spot and the diffusion changes more with the viewing angle, compared to projection screen C (Figure 4.3).



**Figure 4.3** Projection screen D

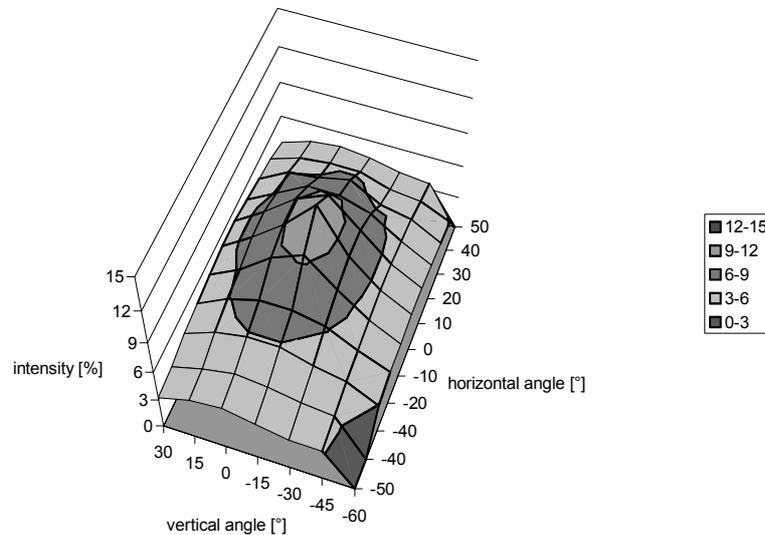
Next, two different types of PDLC panels were analyzed. The first one is referred to as glass panel A. The PDLC film is laminated between two sheets of uncolored glass. All measurements were done in the off state, where the PDLC glass panel is in the opaque state. The measurement shows an evident hot spot and a fast decrease of luminosity with increasing viewing angles (Figure 4.4). The intensity range covers the whole scale from 0% to 100%. The measured distribution could also be verified in practice while viewing the projection. The hot spot was evident and the image faded out considerably while looking towards the edges of the projection.



**Figure 4.4** Glass panel A

The second PDLC glass panel, referred to as glass panel B in this thesis, shows considerably better projection qualities compared to glass panel A (Figure 4.5). The hot

spot is quite limited and the diffusion homogeneity is at an acceptable level. In regards to projection quality, glass panel B is positioned between projection screen C and projection screen D. Also in practice, glass panel B proved to have balanced projection properties and a convincing projection quality.



**Figure 4.5** Glass panel B

The PDLC glass panel B offers the better projection quality of the two tested PDLC glass panels. The glass panel B projection properties are also convincing when compared to other projection screens. Based on these results, it was decided to use the PDLC glass panels B as projection walls in blue-c.

Normally only the reflections on the front side of a projection screen are relevant. In blue-c, where the cameras are positioned behind the screen, both sides are relevant. The reflection on the back side is visible to the cameras. The reflection on the front side is seen from the user and from the opposite cameras. While conventional projection screens have a rough surface on the front side to minimize reflections, switchable projection screens have smooth glass surfaces on both sides since they have to be transparent when the PDLC film switches to transparent. This surface has approximately the same reflection properties as a normal glass panel. The glass panels B are coated with a special anti-reflective coating to minimize these reflections. However, compared to an optimized projection screen, the reflection on the PDLC glass panel is still evident. Dark surroundings help to minimize reflections, especially from the back side. A further improvement can be achieved by switching off the projectors during picture acquisition. Unfortunately, there is very little that can be done in order to reduce the internal reflections. Fortunately, if the reflections are not too dominant, the observers begin to ignore them as soon as they are immersed in the virtual world. The same effect can be observed while watching TV, where most of the time there are many visible reflections which are ignored by the viewer after a short time.

### 4.3 ELECTRICAL PROPERTIES

To change the optical property of a PDLC glass panel, an electrical field has to be applied perpendicular to the PDLC film. A voltage ranging from 50 V to 100 V is necessary in order to generate this electric field. The PDLC glass panels consist of two glass layers,

coated internally with a transparent conductor and a PDLC film in between. Each of the two conductors has to be contacted by an electrode. On the PDLC glass panels which were used, the two copper electrodes are located on the two shorter edges in order to be invisible when the glass panels are installed. The current through the transparent conductor has to be limited to avoid overheating, which would damage the PDLC glass panel. The manufacturer of glass panel B recommends not exceeding 300 mA for a 2240 mm x 950 mm panel when the electrodes are placed on the short edges, as installed in blue-c.

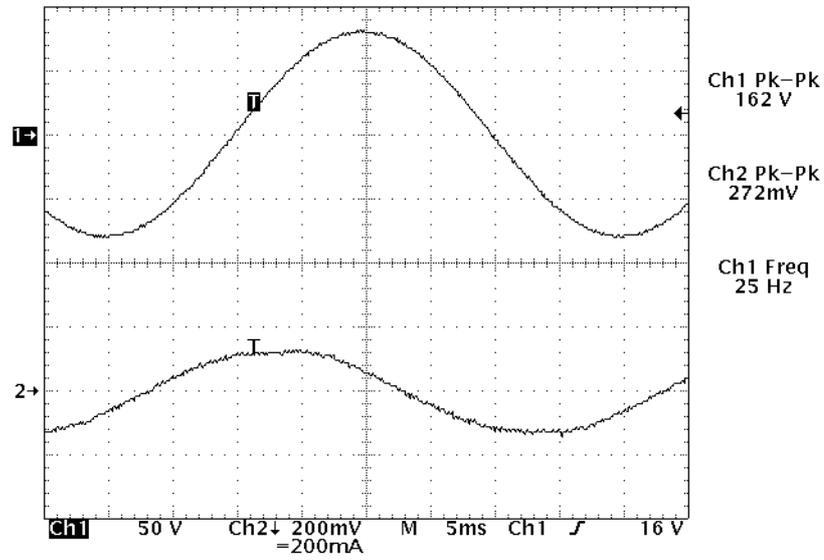
Relatively few studies about the electrical properties of PDLC films have been done so far. P. Drzaic [32] suggests reproducing the electrical behavior of PDLC panels by a three component circuit consisting of two resistors and one constant capacitor as shown in Figure 4.10. Vaz and Montgomery [33] basically present the same three-component circuit but with a variable capacitor  $C$ , where the value depends on the operating voltage  $V_{\text{rms}}$  but not on the frequency. This voltage dependency is present at low voltages and is not relevant for voltages around the normal operating point. The electrical properties of PDLC panels are determined by the physical construction of the whole device and the capacitance  $C$  is a linear function of the surface area of the panels.

#### 4.3.1 Measurements on the PDLC Glass Panels

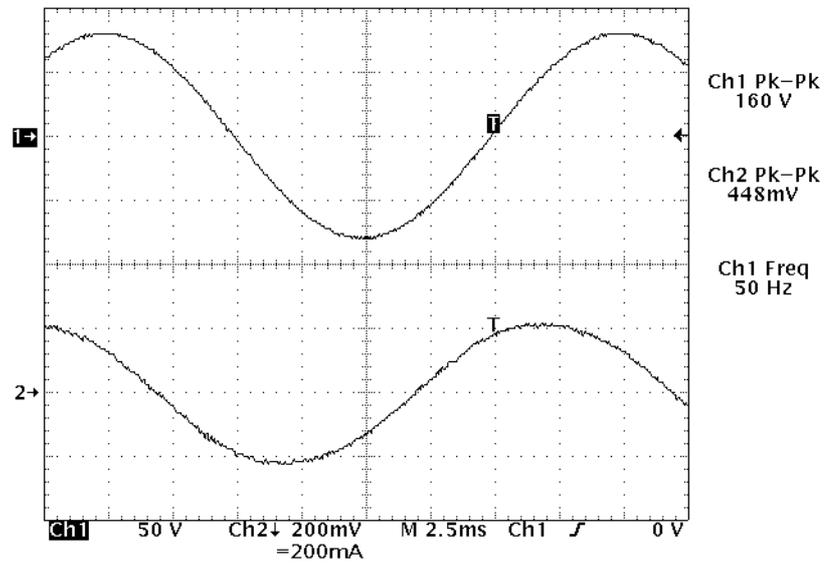
In order to analyze the electrical properties of the PDLC panels, the current response to an applied voltage was measured. As with other liquid crystal devices, the PDLC panels should not be exposed to any DC voltage to prevent ionic buildup, which damages the structure of the liquid crystals. Therefore, only AC measurements were performed. There is also an upper frequency limit given by the maximum allowed current. For a voltage of 80 V the maximum frequency is around 100 Hz. By further increasing the frequency, the current would also increase and thus damage the PDLC glass panels at some point.

The current response to a sinusoidal voltage with an amplitude of 80 V was measured. The measurements were done at frequencies of 25 Hz (Figure 4.6), 50 Hz (Figure 4.7) and 100 Hz (Figure 4.8). The figures show the measured voltages in the upper channel (Ch1) and the measured currents in the lower channel (Ch2). A small shunt resistor was connected in series with the glass panels to measure the currents. A current through the

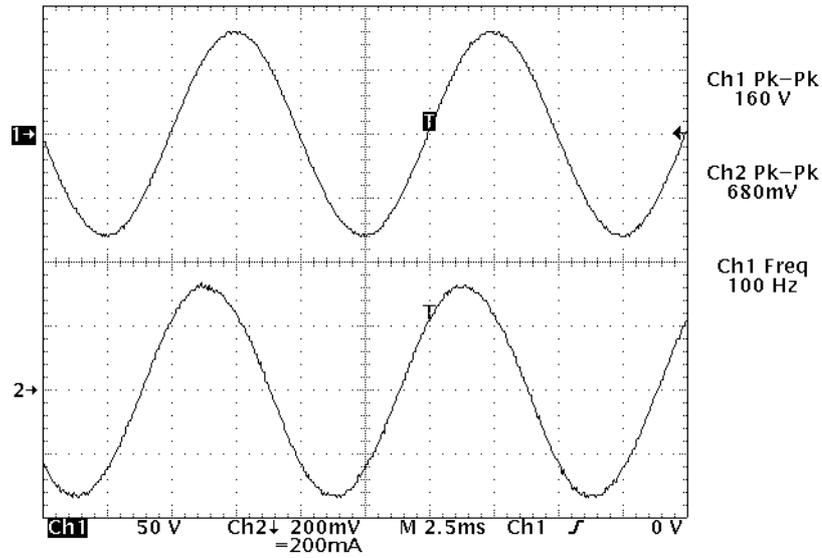
resistor causes a small voltage drop over the resistor, which can be measured. For the resistor which was used, a voltage drop of 1 V corresponds to a current of 1 A.



**Figure 4.6** Voltage and current measured on a PDLC glass panel B at 25 Hz

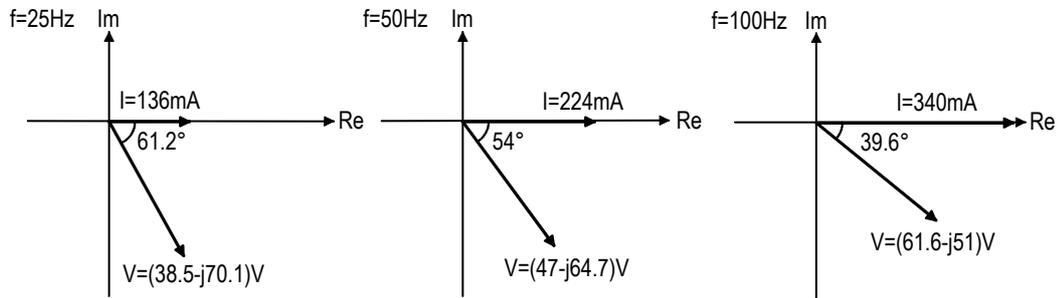


**Figure 4.7** Voltage and current measured on a PDLC glass panel B at 50 Hz



**Figure 4.8** Voltage and current measured on a PDLC glass panel B at 100 Hz

As can be seen from the measurements, the current is preceding the voltage. This is caused by the capacitive component of the PDLC glass panel. The measured voltages and currents can be projected onto the complex plane. Figure 4.9 shows the complex plane for the three measurements with the respective voltage and current vectors.



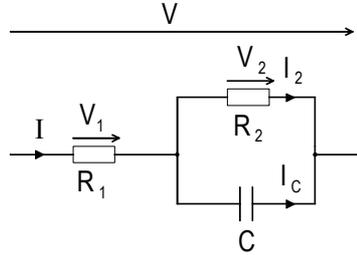
**Figure 4.9** Voltages and currents of the measurements in the complex plane

The extracted values from the three measurements, including the complex values for the voltages, are listed in Table 4.1. The complex voltage values have been extracted under the assumption that the currents are on the real axis and therefore do not have any imaginary components. This choice is advantageous for later calculations.

**Table 4.1** Measurements glass panel B of 2240 mm x 950 mm

f	25 Hz	50 Hz	100 Hz
V (amplitude)	80 V	80 V	80 V
I (amplitude)	136 mA	224 mA	340 mA
$\alpha$ (phase)	61.2°	54°	39.6°
V (complex)	$(38.5 - j70.1) V$	$(47 - j64.7) V$	$(61.6 - j51) V$

The current is ahead of the voltage which indicates that the equivalent circuit should include a capacitance. The phase shift angle  $\alpha$  between current and voltage is well below  $90^\circ$  for the measured frequencies, therefore, some resistive components also have to be integrated in the equivalent circuit. An equivalent circuit of three components as proposed by P. Drzaic [32] is used (Figure 4.10).



**Figure 4.10** Equivalent circuit diagram of the PDLC glass panel

### 4.3.2 Analysis of the PDLC Glass Panels

With the measurements it is now possible to determine the values of the components. The electrical relations are listed in the following equations:

$$V = V_1 + V_2 \quad (4.1)$$

$$V_1 = R_1 \cdot I \quad (4.2)$$

$$V_2 = R_2 \cdot I_2 \quad (4.3)$$

$$V_2 = \frac{1}{j\omega C} \cdot I_C \quad (4.4)$$

$$I = I_2 + I_C \quad (4.5)$$

Equations 4.3 to 4.5 can be combined to

$$I = I_2 + I_C = V_2 \cdot \frac{1}{R_2} + V_2 \cdot j\omega C = V_2 \cdot \left( \frac{1}{R_2} + j\omega C \right) \quad (4.6)$$

and be rewritten to

$$V_2 = I \cdot \frac{1}{\frac{1}{R_2} + j\omega C} = I \cdot \frac{R_2}{1 + j\omega CR_2} \quad (4.7)$$

Equations 4.1, 4.2 and 4.7 are combined to:

$$\begin{aligned}
V &= V_1 + V_2 = I \cdot \left( R_1 + \frac{R_2}{1 + j\omega CR_2} \right) \\
&= I \cdot \left( R_1 + \frac{R_2 \cdot (1 - j\omega CR_2)}{1 + (\omega CR_2)^2} \right) \\
&= I \cdot \left( R_1 + \frac{R_2}{1 + (\omega CR_2)^2} - j \cdot \frac{\omega C \cdot (R_2)^2}{1 + (\omega CR_2)^2} \right)
\end{aligned} \tag{4.8}$$

Under the premise that the current  $I$  only has a real and not an imaginary component, Equation 4.8 can be separated into an equation for the real components and an equation for the imaginary component of  $V$ .

$$V_{re} = I \cdot \left( R_1 + \frac{R_2}{1 + (\omega CR_2)^2} \right) \tag{4.9}$$

$$V_{im} = -I \cdot \frac{\omega C \cdot (R_2)^2}{1 + (\omega CR_2)^2} \tag{4.10}$$

We now have two equations with a total of three parameters to determine, namely  $R_1$ ,  $R_2$  and  $C$ . With the three measurements, as listed in Table 4.1, an approximation is done. The mean square error (MSE) between the calculated voltage vectors and measured voltage vectors is minimized. The approximated values are

$$R_1 = 174.5\Omega, \tag{4.11}$$

$$R_2 = 2494\Omega, \tag{4.12}$$

and

$$C = 11\mu F. \tag{4.13}$$

Table 4.2 shows the calculated voltages in comparison to the measured voltages.

**Table 4.2** Measured versus calculated voltages

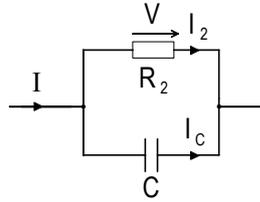
f	25 Hz	50 Hz	100 Hz
I	136 mA	224 mA	340 mA
V (measured)	(38.5 - j70.1) V	(47 - j64.7) V	(61.6 - j51) V
V (calculated)	(39.8 - j72.4) V	(46.5 - j63.9) V	(61.4 - j48.4) V
$ \Delta V $ (error)	2.60 V	1.03 V	2.64 V

$R_1$  and  $C$  are the dominant components. However, the value of  $R_2$  is still important therefore it should not be neglected. The calculated value of  $C$  is also in accordance with the measurements of N. Vaz and P. Montgomery [33], who measured a capacitance of  $4.6 \mu F/m^2$ .

In the following section two simplified equivalent circuits, derived from the three component circuit, are analyzed. This analysis is done by looking at the voltage response

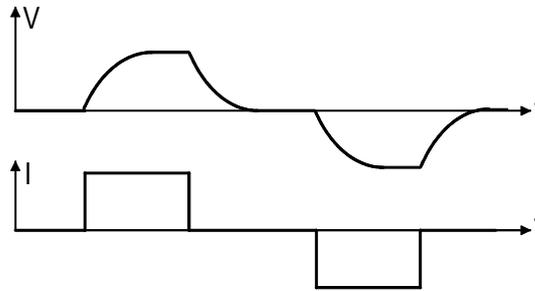
to a given current input. In the first case,  $R_1$  is omitted whereas in the second case  $R_2$  is omitted. This achieves a better understanding of the reaction of the PDLc panels when being actively triggered. The circuits were only qualitatively analyzed. The real behavior of a PDLc glass panel is a combination of the two analyzed simplified circuits.

$R_1=0$ . By setting  $R_1$  equal zero the equivalent circuit is reduced to  $R_2$  and  $C$  as shown in Figure 4.11.



**Figure 4.11** Two component equivalent circuit consisting of  $R_2$  and  $C$

The response to a positive and negative current jump can be seen in Figure 4.12.



**Figure 4.12** Voltage response of the  $R_2$ - $C$  circuit to a positive and negative current jump

Immediately after the current has jumped from zero to a positive or negative value, almost the entire current flows into the capacitor  $C$  thereby charging it (Equation 4.14).

$$V(t) = I \cdot R_2 \cdot \left( 1 - e^{-\frac{t}{R_2 C}} \right) \quad (4.14)$$

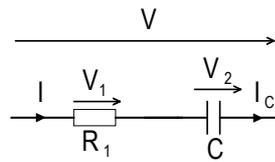
With rising voltage, the amount of current flowing through the resistor increases until the point where all of the current is flowing through the resistor and no more current is charging the capacitor  $C$ . The voltage at this point has a value of

$$V = I \cdot R_2 \quad (4.15)$$

The voltage remains at this value until the current is switched off. From this time on, the capacitor  $C$  is discharged over the resistor  $R_2$  (Equation 4.16).

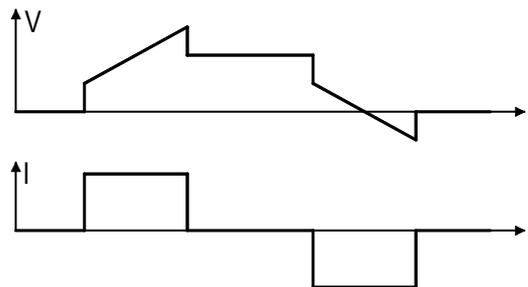
$$V(t) = V(t=0) \cdot e^{-\frac{t}{R_2 C}} \quad (4.16)$$

$R_2 = \infty$ . For the following analysis, the resistor  $R_2$  of the three components circuit is set to infinite (Figure 4.13).



**Figure 4.13** Two-component equivalent circuit consisting of  $R_1$  and C

The response to a positive and negative current jump can be seen in Figure 4.14.



**Figure 4.14** Voltage response of the  $R_1$ -C circuit to a positive and negative current jump

The voltage response of the two components,  $R_1$  and C, can be analyzed separately and added afterwards. The voltage over the resistor  $R_1$  is proportional to the current flowing through it. The voltage over the capacitor C increases linearly with a positive current and decreases linearly with a negative current. The superposition of the two voltages gives the response of the circuit (Equation 4.17).

$$V(t) = V(t=0) + I \cdot R_1 + \frac{1}{C} \cdot I \cdot t \quad (4.17)$$

The capacitor, assumed to be ideal, keeps its voltage after the current is switched off.

### 4.3.3 Electrical Control

In blue-c, the PDLC glass panels are switched between the transparent and opaque states. The electronic control connected to the PDLC glass panels, therefore, has to switch the voltage on and off.

**Figure 4.15 a and b.** Theoretically, a square wave signal would be sufficient (Figure 4.15 a). In order to remove DC components from the glass panels, which would damage them, the square wave should be alternately composed of positive and negative squares (Figure 4.15 b). If a square wave is connected to a capacitive load, the current during transition can be very high and thus damage the PDLC glass panels. Therefore, a current limit control has to be superimposed onto the voltage control. For the installed panels the limit was set to 300 mA per panel, which is in accordance with the manufacturer's suggestions.

**Figure 4.15 c.** Figure 4.15 c shows the voltage and current for a control with current limitation. Just after turning on the voltage, which tries to jump to its prefixed value, the current jumps to the set limit. The voltage also performs a jump at the beginning,

determined by the resistive component  $R_1$ . This voltage jump is then followed by a linear charge of the capacitor (slow voltage increase), up to the point where the voltage applied to the PDLC panels reaches the maximum value set by the electronic control. From that point on, the current starts to drop towards the value implied by the two resistors  $R_1$  and  $R_2$  in series (Figure 4.10).

To switch off the PDLC panels, the control tries to switch the voltage applied to the glass panels back to zero. The current immediately jumps to its prefixed negative limit. As a consequence, the voltage across  $R_1$  drops in correspondence to the current jump. Now the positive charged capacitor starts to discharge. At some point the voltage on the glass panel reaches zero, while the capacitor is still discharging as can be seen from the current.

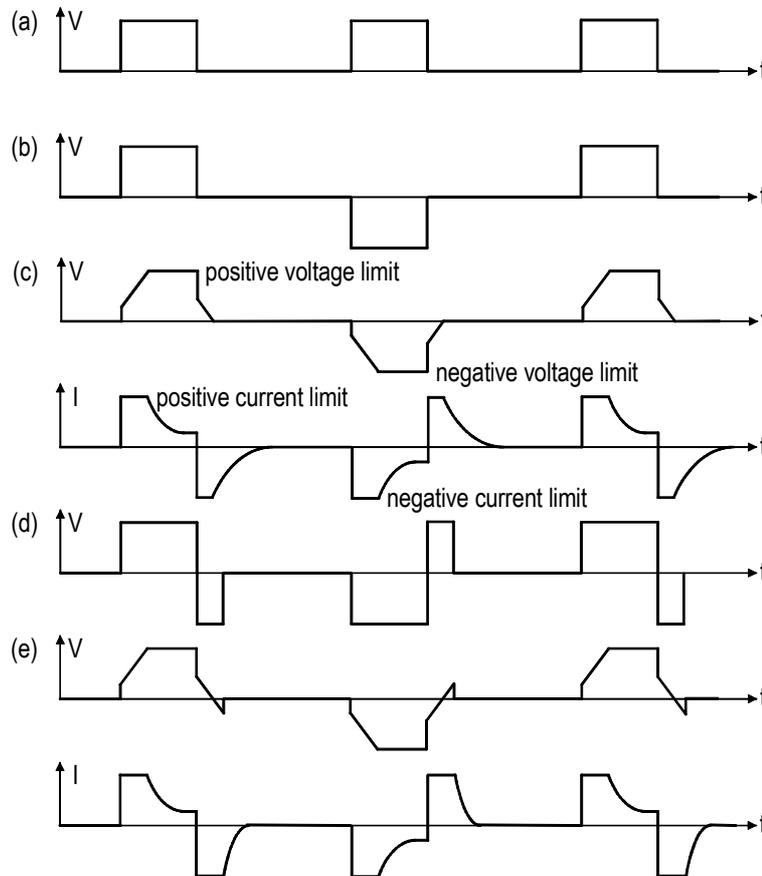
For the next triggering cycle, the same behavior can be seen but with inverse voltages and currents.

**Figure 4.15 d.** It is possible to improve the discharging of the capacitance, while turning off the PDLC panels. To do this, the electronic control follows a positive voltage signal by a short negative voltage pulse and vice versa. Figure 4.15 d shows the voltage as if there were no current limitation superimposed onto the voltage control.

**Figure 4.15 e.** In Figure 4.15 e the same voltage sequence of Figure 4.15 d is shown, but with a superimposed current limitation. The voltage change is, therefore, slowed down, as soon as the current limit is reached. The new short pulses of opposite polarities keep the discharging current at its maximum limit for a longer period of time thus discharging the capacitance faster than in Figure 4.15 c. While measuring the voltage at the glass panel, the discharging voltage ramp is longer, thus getting negative. The voltage then jumps immediately back to zero after the electronic control turns off the negative voltage pulse. The remaining voltage in the capacitor is lower, resulting in a shorter discharge time. The same behavior can be seen for the next negative triggering cycle.

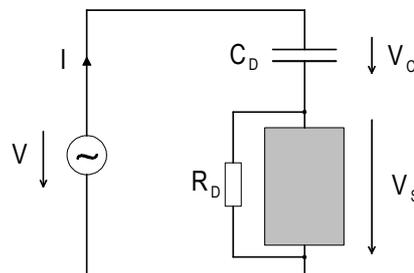
It is important that both the voltage and the current are limited to protect the PDLC glass panels from damage. A voltage which exceeds the set parameters would cause an

electric breakdown of the PDLC film and an exceeding current would overheat the conductive layer of the glass panel.



**Figure 4.15** Active triggering methods

The PDLC glass panel control electronics of blue-c generate a DC free driving voltage. In addition, an external DC decoupling circuit was added to guarantee that no DC voltage damages the glass panels, even if a defect in the driving circuit occurs. This DC decoupling consists of a capacitor  $C_D$  and a resistor  $R_D$  (Figure 4.16).



**Figure 4.16** DC decoupling

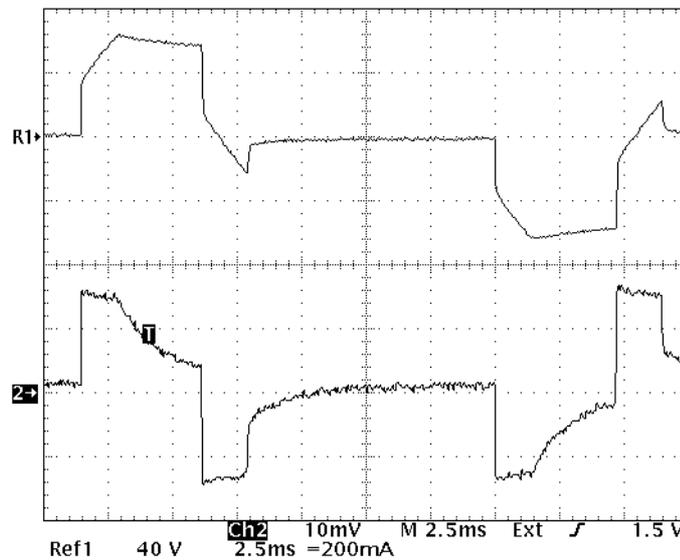
The values of  $60 \mu\text{F}$  for the decoupling capacitor  $C_D$  and  $10 \text{ k}\Omega$  for the resistor  $R_D$  were chosen. The value of  $60 \mu\text{F}$  is large enough compared to the capacitance of the glass panels, which is  $11 \mu\text{F}$ . The voltage drop over the decoupling capacitor  $C_D$  is, therefore, limited to about 15% of the total applied voltage. The resistor  $R_D$  also causes a small unwanted discharge of the capacitor  $C_D$  between the different voltage pulses. With a value

of  $10\text{ k}\Omega$ , this ripple can be restricted to less than  $2\text{ V}$ . The resistor  $R_D$  is actually not necessary with the glass panels B, because it is higher than the internal resistance. Nevertheless, it was mounted in case the glass panels B would be replaced by some other PDLC panels with a higher resistance.

For further details of the electronic circuit refer to chapter 6.

#### 4.4 MEASUREMENTS ON AN ACTIVELY TRIGGERED PDLC GLASS PANEL

The measurements have been done on a glass panel B, which was installed in blue-c. The glass panel was triggered by the custom-made synchronization control. The PDLC was turned on and off with a frequency of  $62.5\text{ Hz}$ . The triggering pattern of Figure 4.15 d was used with a first square of  $4.6\text{ ms}$  followed by an opposing pulse of  $1.7\text{ ms}$ . The measurements of Figure 4.17 show two switching cycles. The upper measurement shows the voltage on the glass panel and the lower measurement shows its current, measured with a clamp-on ammeter. The small offset in the current is caused by a measurement error.



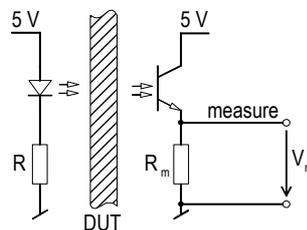
**Figure 4.17** Active triggering of glass panel B

As can be seen in the previous Figure, the current stays between a set limit of  $300\text{ mA}$  and  $-300\text{ mA}$ . The voltage limits are approximately set to  $65\text{ V}$  and  $-65\text{ V}$ . The effective voltage limits of the electronic control are actually set higher than that. However the additional decoupling capacitor, as shown in Figure 4.16, causes a voltage drop of  $15$  to  $20\%$ . This voltage drop can easily be compensated for by setting the control voltage to the desired value. The voltage and current measurements of Figure 4.17 were done directly on the glass panel and thus measured only the values applied on the panel itself.

Starting from the left in Figure 4.17, the measurement shows how the current jumps to the limit of  $300\text{ mA}$  after starting to switch the PDLC panels to transparent. The voltage starts with a jump, followed by a slope. After the voltage has reached its maximum value, the current is gradually reduced. The control, at this point, keeps the voltage at the preset maximum value. Whereas in the measured voltage, a small decrease can be observed. This decrease is caused by the decoupling capacitor  $C_D$  connected in series with

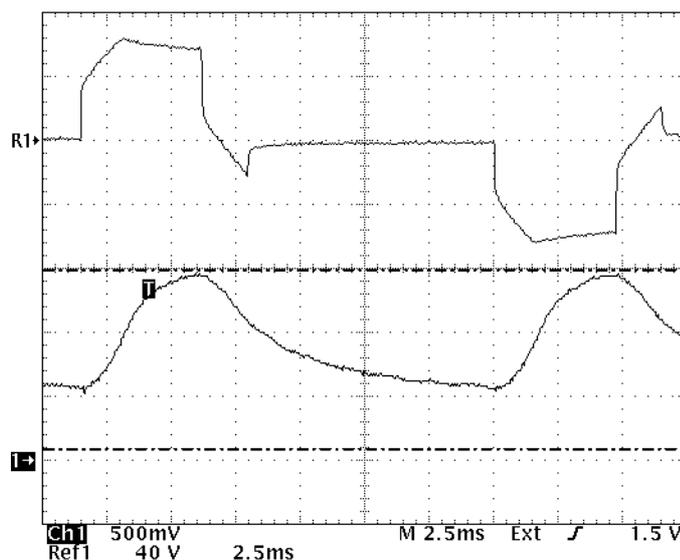
the internal resistance of the PDLC glass panel. The big resistor  $R_D$  in parallel with the internal resistance of the PDLC glass panel only has a small influence on this voltage decrease. In the next step, the voltage is switched to negative. Again the current response is immediate and reaches the negative limit of -300 mA this time. After 1.7 ms the voltage is then switched back to zero and a small amount of current discharges the remaining charge of the capacitances.

The optical response of the glass panel B is shown in Figure 4.19. The same triggering pattern as in the previous measurement was used. The transparency was measured with a photo transistor installed at a distance of 4 cm from the glass panel. This photo transistor was illuminated with a white LED from the opposite side of the glass panel (Figure 4.18). Depending on the transparency of the glass panel, more or less light gets defused thereby changing the amount of light measured by the photo transistor. The photo transistor was then connected in series with a 2 k $\Omega$  resistor and driven with a 5 V power supply.



**Figure 4.18** Optical measurement circuit

The dotted lines in Figure 4.19 represent the level of transparency in the continuous opaque state (lower line) and the continuous transparent state (upper line). These two levels are defined as 0% and 100% transparency. The measurement plotted between the two dotted lines represents the optical response to the triggering voltage as seen in the upper section of Figure 4.19. The driving frequency is 62.5 Hz and the duty cycle is 0.2875 (4.6ms/16ms). In this case, the transparency of the glass panel varies from 34% to 97%.

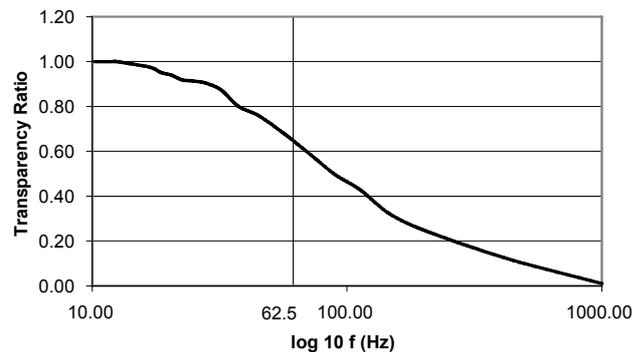


**Figure 4.19** Optical response glass panel B

As can be seen from the measurements, the change from opaque to transparent is much faster than the change from transparent to opaque. With a higher voltage or a higher current limit (if allowed), the transition from opaque to transparent could be accelerated. However, there is not much that can be done to accelerate the transition from transparent to opaque. This transition is determined by the internal relaxation forces of the PDLC film and thus can not be influenced electrically. The image acquisition with the camera has to be exactly synchronized with the switching of the PDLC panels and the shutter speed should be around 2 ms for a good quality picture.

The driving voltage has been optimized for the simultaneous projection and picture acquisition with PDLC glass panels B. In order to switch the PDLC panels, a low frequency would be desirable. On the other hand, the frequency must be high enough to allow projection and image acquisition without causing any flickering that would be disturbing for the user. A frequency of 62.5 Hz allows a flicker-free projection while still allowing an adequate operation of the PDLC panels (Figure 4.20).

The transparency ratio of Figure 4.20 has been normalized in relation to the minimal and maximal achievable transparency levels of the PDLC glass panel. The plotted value in the chart is the difference between the maximum and the minimum transparency which is achieved during one cycle measured at the corresponding frequency, divided by the difference between the maximum and minimum achievable transparency of the PDLC glass panel. The maximum and minimum achievable transparency of the glass panel is marked with dotted lines in Figure 4.19.



**Figure 4.20** Frequency response of the PDLC panel B with 0.2875 duty cycle

The operating voltage was also optimized to reach a high transparency of the PDLC panels in combination with a fast response time. Higher voltages would slow the transition from transparent to opaque, while lower voltages would decrease the maximum transparency.



## FLASH ILLUMINATION

The requirements for the blue-c illumination are very demanding. For the projection of images, the inside as well as the outside of the projection room have to be dark. On the contrary, bright illumination is important for good image acquisition. The illumination has a big impact on the quality of the extracted silhouettes and acquired textures of the user. A person inside blue-c should be illuminated uniformly from all sides and shadows should not be projected on the floor. The illumination has to be directed away from the PDLC glass panels to avoid loss of contrast. The reason being that the PDLC glass panels acquire gray shading when they are illuminated with bright light.

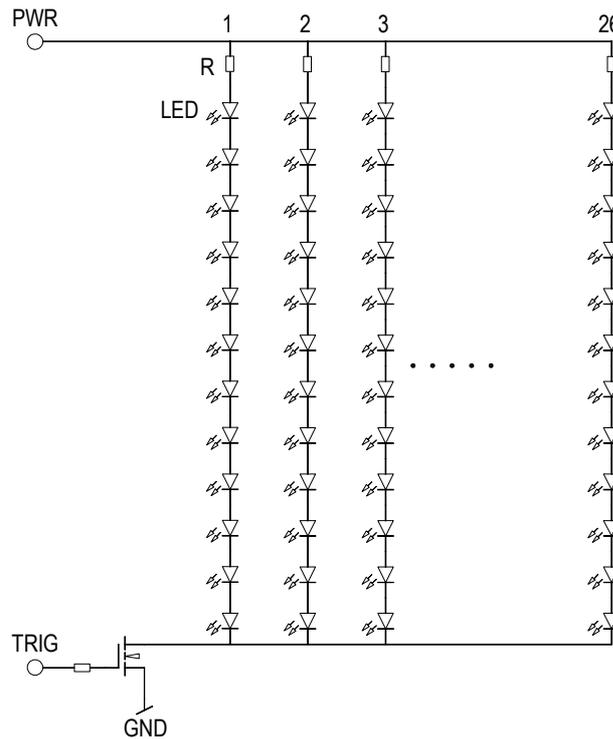
An active illumination is used to satisfy both needs of projection and image acquisition. The active light is off during projection and is on during the image acquisition. Therefore the light has to provide illumination for only a few milliseconds and must be capable of turning on and off with a frequency between 60 and 70 Hz. Initial tests were done with a strobe light. A high voltage discharge in a Xenon flash lamp produces a bright light pulse with a very short duration. Frequencies in the range of 60 Hz are not a problem for this type of lamp. Despite the ability to switch quickly, this type of light has some important disadvantages. Light is emitted for only a few microseconds and the light intensity integrated over time is therefore mediocre. The high voltage discharge in a very short time period causes heavy electromagnetic pulses, which can interfere with surrounding electronic components. The discharges also cause a disturbing acoustic noise. In addition, the strobe light is quite large. This is a handicap when trying to distribute the light uniformly in the projection room. All of these disadvantages determined that another illumination solution was needed.

### 5.1 ACTIVE LED ILLUMINATION

The requirement of short switching times considerably restricts the number of suitable light sources. Light Emitting Diodes (LEDs) have very short switching times and are thus suitable for our application. The first LED was developed in 1967 and produced a red light. Some more colors were created in the following years, but it was not until 1996 that the first white LED was developed [38]. Today white LEDs are widely available and the light efficiency is about twice that of an incandescent bulb [39]. LEDs can easily

be grouped into clusters in order to output more light. The clusters are flat, can be of any shape and the light output can be distributed homogeneously over the cluster if desired. These facts in combination with the absence of current and voltage peaks, which cause electromagnetic interferences, make the LED the first choice for blue-c.

A total of 9,984 white LEDs have been integrated into blue-c. The 5 mm model (NSPW510BS SB) from Nichia was chosen. The opening angle (50% intensity) is  $50^\circ$  and the light output is approximately 2,200 mcd per LED. These LEDs were among the brightest available on the market in 2002. The LEDs are configured into 32 clusters, each of them containing 312 LEDs. The clusters are reassembled in groups of two, four or five and mounted in long aluminum U-profiles.

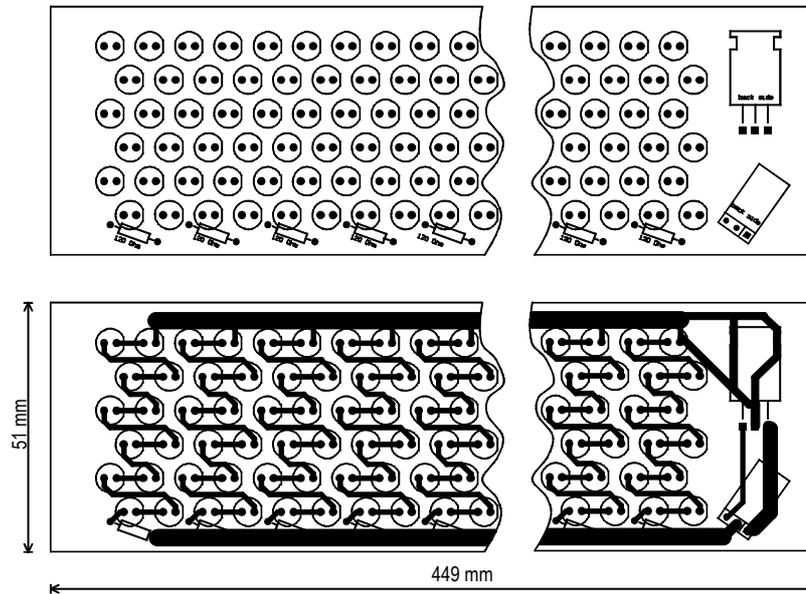


**Figure 5.1** LED cluster

The LEDs have a nominal current of 20 mA at a voltage drop of about 3 V. The question was posed regarding the number of LEDs which should be connected in parallel and the number which should be connected in a series. By connecting all LEDs in parallel, a current of nearly 200 A would be required. Besides the thick cables and expensive power supply which would be necessary, the switching of this high current would be a challenge due to parasitic inductance. In addition, many LEDs arranged in a series would increase the voltage applied and in case of a defect, the whole series of LEDs would stay black. It was decided to make series of 12 LEDs. The voltage is maintained below 48 V with this configuration, which allows compatibility with a wide variety of power supplies and furthermore only requires low voltage isolation. The electrical circuit of a cluster is displayed in Figure 5.1. Each of the 26 LED rows has a resistor of  $120 \Omega$  connected in series to limit the current in the row. A MOSFET is integrated into each cluster to switch the LEDs on and off. The clusters are driven with a voltage of 37.5 V and the total current consumption of all 32 clusters together is 16.6 A in the on state. Because of the integrated MOSFETs in the LED clusters, only a synchronization signal is needed to turn the LEDs on and off. The clusters are directly connected to the power supply which is

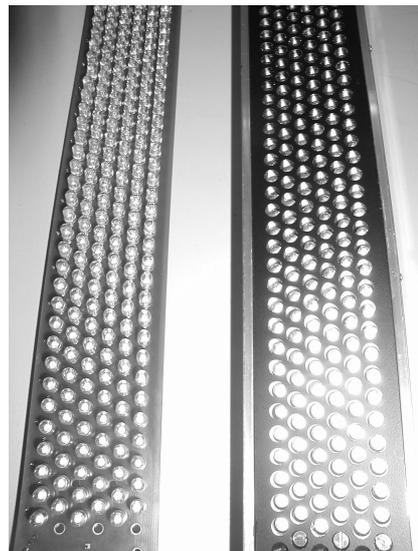
placed in the floor of the projection room to minimize the length of the high current connections and thus the magnetic fields.

The LEDs are geometrically arranged in 6 rows of 52 LEDs per cluster. Figure 5.2 shows the printed circuit board (PCB) of the LED array with and without the copper layer. Each board is populated with 312 LEDs, 26 resistors, one connector and one MOSFET.



**Figure 5.2** LED printed circuit board

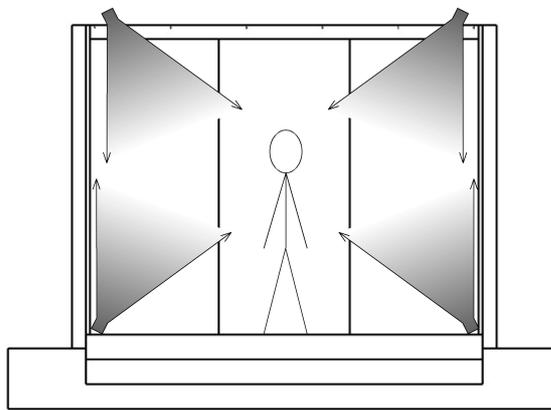
A black polyethylene mask is mounted in front of each cluster to minimize the amount of unwanted scattered light. A 6 mm hole for each of the LEDs has been drilled into the mask with a CNC milling machine. The LED clusters have been mounted in groups, together with the masks, into aluminum profiles. On the left side of Figure 5.3, the populated PCB of a LED cluster is depicted and on the right side, the LED cluster mounted into an aluminum profile together with the mask is depicted.



**Figure 5.3** LED cluster PCB board with and without mask

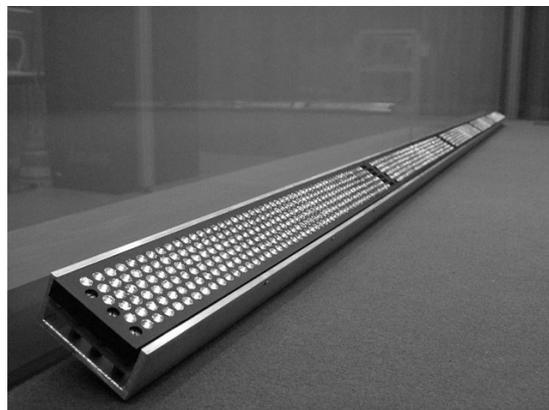
The LED clusters have to be carefully placed in blue-c to ensure a good image acquisition. The cameras are mostly placed outside of blue-c and are positioned more or less horizontally to the user through the PDLC glass panels. Regarding this aspect, a diffused frontal illumination of the user would be most suitable. But a frontal light would also shine directly into the opposite cameras and would furthermore put too much light on the glass panels thereby making them appear to be gray. In addition, it would be difficult to find a location for mounting 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 illuminate the front side of the user, which at the same time minimizes the amount of light directed to the glass panels and to the opposite cameras. The additional mask in front of the LEDs helps to further diminish the amount of scattered light that reaches the glass panels. Figure 5.4 shows a person between two opposite projection walls, as is the case in blue-c for the two side walls. The light is coming from all four edges and the majority of the person is illuminated by the light sources.



**Figure 5.4** Placement of the LED clusters

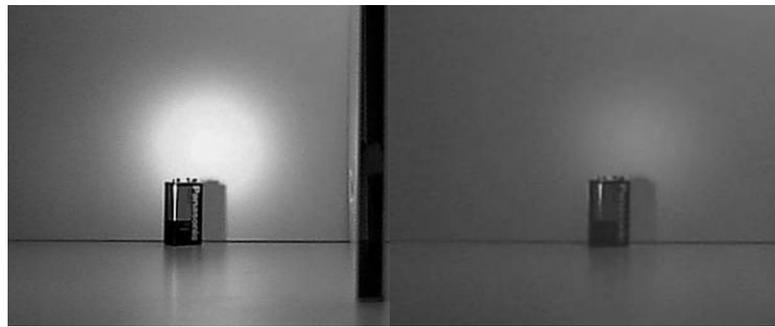
This figure depicts the placement of the bottom left illumination clusters. Five of them are integrated into the aluminum profile and placed in the edge between the floor and the left glass panels.



**Figure 5.5** Placement of the LED clusters in blue-c [41]

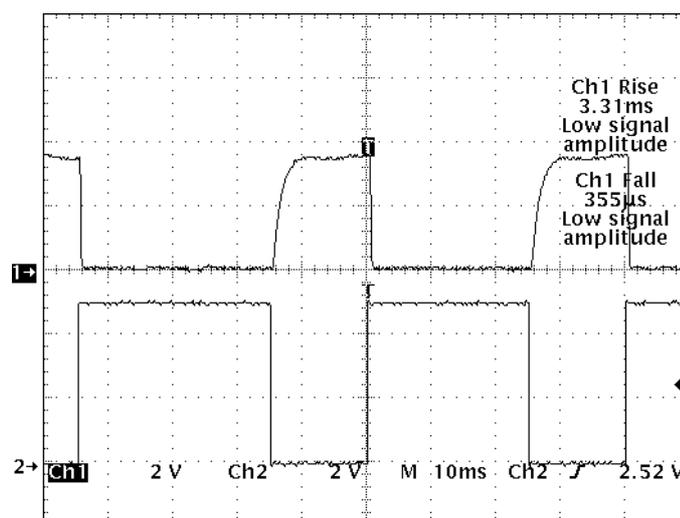
## 5.2 MODIFIED SHUTTER GLASSES

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 blue-c considerably diminishes the contrast of the projected image. To protect the user from the active light, an apposite third phase has been integrated into the stereo glasses to block the light from the user's eyes [42]. The projection of the left and the right eye images are followed by a third phase, at which both LC shutters of the glasses are darkened [43]. The LED illumination is only on during this phase. This helps to fade out most of the light from the illumination. Figure 5.6 shows two images of a 9 V battery, both illuminated with a strobe light. The image on the left has been taken through a non-synchronized shutter glass whereas the image on the right has been taken through a synchronized shutter glass. As can be seen in the image on the right, almost all of the light from the strobe has been removed.



**Figure 5.6** Flash with and without synchronized shutter glasses

The shutter glasses used in blue-c and the IR emitter have a built-in microcontroller. They were reprogrammed to integrate the third phase. Like most shutter glasses, the blue-c glasses use TN LC shutters. With these shutters, the transition from transparent to black is quite fast, whereas the black to transparent switching time takes considerably longer. Figure 5.7 shows the switching time of the shutter glasses.



**Figure 5.7** Optical response of 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 measurements, there is not a relevant delay between applying 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 whereas the switching from 90% to 10% transparency takes less half a millisecond. These values correspond to the values of other shutter glasses as measured by Woods and Tan [18]. For practical use, there is a work around by adding some blanking time between the left eye and right eye projections.

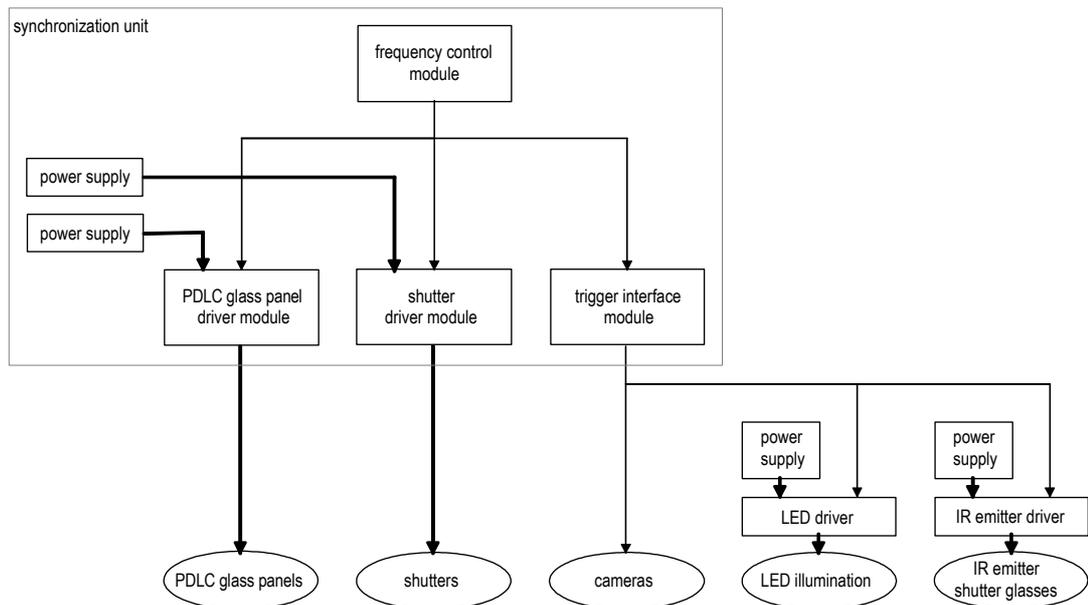
## SYNCHRONIZATION ELECTRONICS

Synchronization electronics are needed in order to have the stereo projection running quasi-simultaneously in combination with the PDLC glass panels, the shutter glasses, the LED illumination and the cameras. Some components need a 5 V TTL triggering signal. Others, like the active projection screens, require higher switching voltages and additional control features like current limitation. Custom-made synchronization electronics were built to satisfy the different requirements of the components and to allow flexible and accurate triggering timings.

The synchronization electronics of blue-c were built modularly to offer the flexibility which is necessary for 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 which drives the other modules of the synchronization unit. Three PDLC glass panel driver modules, two shutter driver modules and one trigger interface module are integrated in the synchronization unit in conjunction 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 6.1 gives an overview of the synchronization electronics. All modules of the synchronization unit are interconnected by 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 along with their own power supplies. The advantage of this setup is that the connections with

hard switched currents, as required to switch the LED clusters, are kept as short as possible.



**Figure 6.1** Synchronization electronics

## 6.1 MODULES

The different modules of the synchronization unit are all connected to the same data and power bus. Except for the frequency control module, all of the modules offer the option to select the different data lines that can be used to trigger the modules. This arrangement offers more flexibility to add other modules or to use additional modules which can be triggered either from the same data line as another module or from a separate data line. The details of the different modules are explained in the following subchapters. Simplified circuit diagrams of the modules are used to explain their function. The complete schematics of these circuits can be found in Appendix B.

### 6.1.1 Frequency Control Module

The frequency control module uses a PIC 16F877 microcontroller from Microchip. This microcontroller can be reprogrammed in-circuit, which means that it can be reprogrammed without unplugging the chip from the board. The board has an integrated RJ 12 connector for programming the microcontroller. Microchip provides an interface for connecting the RJ 12 port of the module to the RS 232 port of the computer.

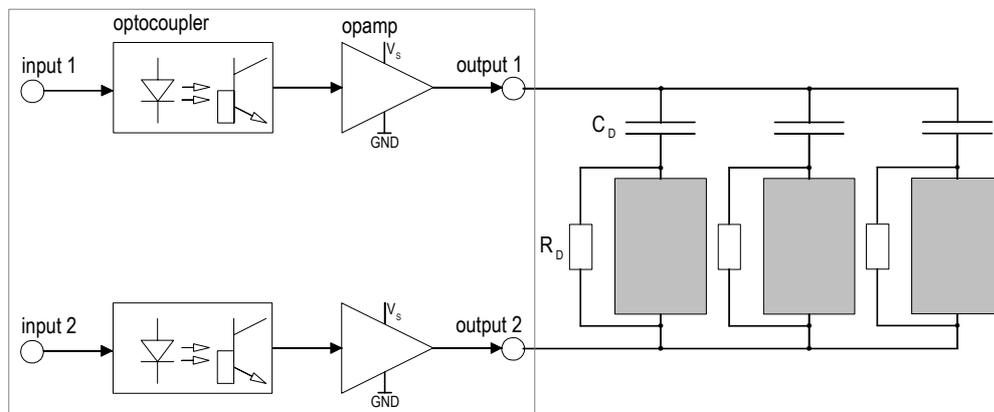
The twenty-two output/input ports of the microcontroller are mapped to the data bus. They can be individually set as outputs or inputs. Each of these ports is connected to a LED to show its state. The microcontroller is clocked with a frequency of 20 MHz to offer high timing accuracy.

### 6.1.2 PDLC Glass Panel Driver Module

A voltage of approximately 65 V has to be applied to the glass panels to switch them to transparent. The voltage has to be DC free, therefore alternating pulses are used to trigger

the glass panels, as explained in subchapter 4.3.3. Furthermore, the maximum current applied per glass panel has to be limited to 300 mA as prescribed by the manufacturer.

A total of three glass panel driver modules are used for driving the nine PDLC glass panels. Three glass panels, arranged in parallel, are always connected to the two outputs of a module. The two outputs of a module can be separately switched to either 8 V or 85 V. These voltage values have been chosen based on the selected components. If both outputs are switched to the same value, voltage is not 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. This principle enables the generation of a bipolar voltage on the glass panels by using a unipolar power supply. Each of the two outputs is directly switched according to the input coming from the data bus. A current limit control, which is integrated in the operational amplifiers, is superimposed to the voltage switching.



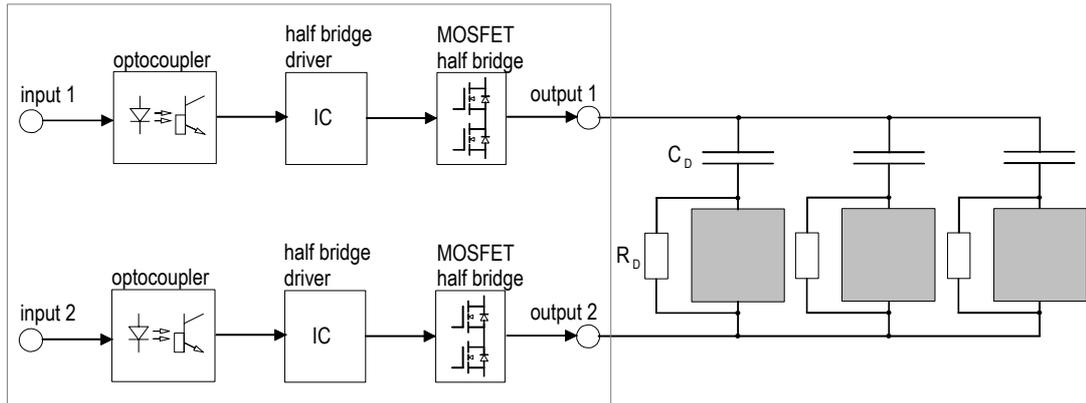
**Figure 6.2** PDLC glass panel driver module

Figure 6.2 shows a simplified circuit of the PDLC glass panel driver module which is connected to three glass panels including the DC decoupling circuits. From the data bus, any two of the data lines can be selected to switch the two outputs of this module. Each of the two incoming TTL signals switches an optocoupler output to a preset voltage of 8 V or 85 V. The optocoupler isolates the PDLC glass panel driver module galvanically from the other modules to prevent damaging them in the event of a defect in the PDLC glass panel driver module. The two outputs of the optocouplers are connected to two APEX PA46 operational amplifiers. The APEX PA64 have an adjustable current limit control which has been integrated 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 only switch between 8 V and 85 V. Thereby giving enough margin from the output voltage of the power supply and ground to prevent saturation of 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.

### 6.1.3 Shutter Driver Module

The shutter driver module has two inputs and two outputs. It consists of two independent circuits. Each of which include an optocoupler, a half bridge consisting of two MOSFETS and a half bridge driver (Figure 6.3). The optocoupler is used to protect the other modules

of the synchronization electronics in case a defect occurs in this module or at a connected component. The output of the optocoupler is connected to a half bridge driver (IR2111), which drives two MOSFETs. The bridge driver assures that the two MOSFETs in the half bridge are never turned on at the same time. The two half bridges have outputs which switch the voltage rail to rail without any current limitation. The module has been designed to switch voltages up to 600 V and currents up to 10 A. The module is operated with a voltage of 12 V in order to drive the Ferro Electric shutters. Three shutters, arranged in parallel, are connected between the two half bridges of a module. The two half bridges are always switched to opposite states. The voltage over the full bridge is therefore either 12 V or -12 V, as required by the shutters for switching.



**Figure 6.3** Shutter driver module

#### 6.1.4 Trigger Interface Module

The triggering interface module is a multi-purpose module. This module is capable of choosing up to eight lines from amongst the 22 data lines of the bus. Each line can be connected to a 5 V or 12 V driver and configured as input or output.

For blue-c, all used channels have been configured as 5 V outputs. One channel is used to trigger the Firewire cameras. A second channel 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. The schematic of the trigger interface module is shown in Appendix B.

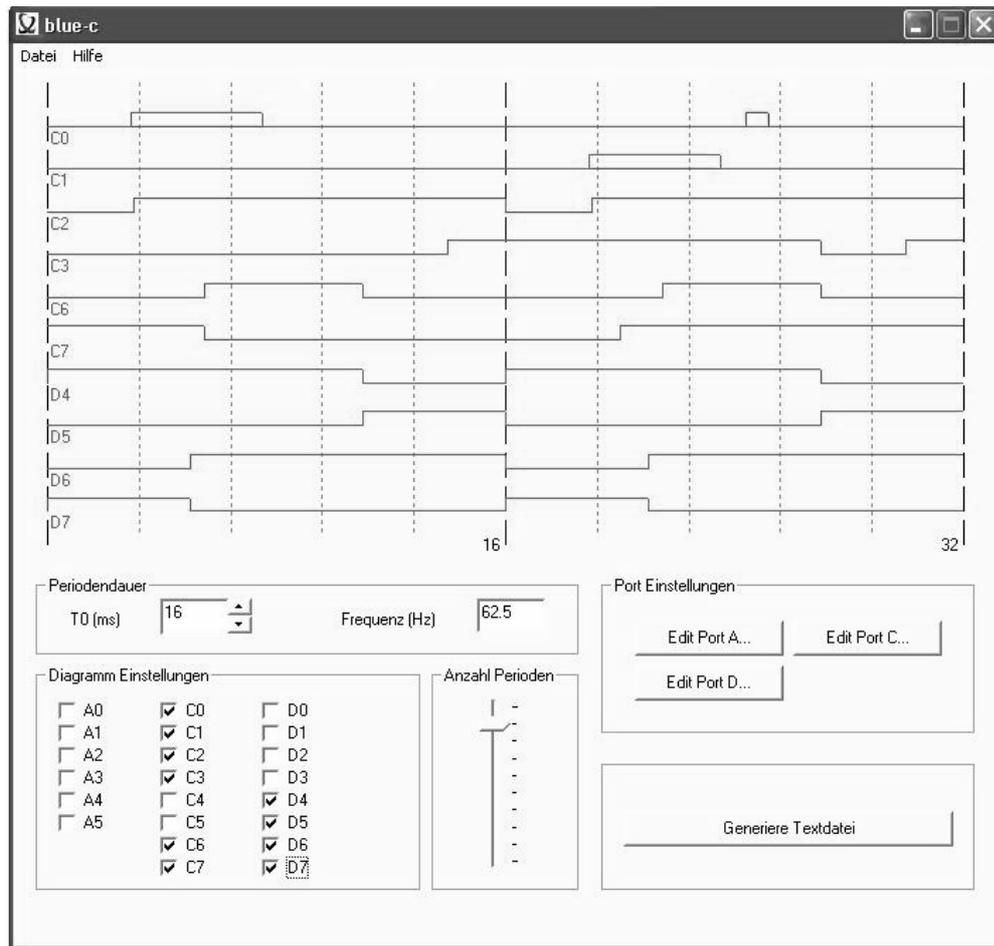
#### 6.1.5 LED Driver

A total of 9,984 LEDs are installed in different clusters in blue-c. The LED clusters have to be driven with a voltage of 37.5 V and a total current of up to 16.6 A. The power supply for the LED cluster is installed in the floor of blue-c and is directly connected to the LED clusters. By directly connecting the power supply to the LED clusters, the wiring distances of the high ampere connections are reduced, which thereby reduces the generated magnetic fields. Furthermore, the inductance caused by long wirings is also kept low, which is important for avoiding voltage spikes caused by fast switching currents. Each cluster has an integrated MOSFET which switches the LEDs on and off (Figure 5.1). The triggering signal comes directly from the trigger interface module.

## 6.2 GRAPHICAL USER INTERFACE TO PROGRAM THE TIMINGS

The PIC 16F877 microcontroller has an 8 kB flash program memory, which can be reprogrammed in circuit. The microcontroller is used for triggering all of the various components of blue-c. In order to have full control of all latencies, it was decided to directly write the program code in assembler code. Nevertheless, to allow quick changes to be made to the triggering patterns, all timing variables are saved in a separate file. The variables in this file can be generated with a dedicated graphical user interface (GUI), which is shown in Figure 6.4 and 6.5. This interface allows the period duration of the trigger cycle to be set. Furthermore, each of the 22 outputs can individually be programmed, when to start (switch to "1"), when to stop (switch to "0") and after which amount of cycles the switching has to be repeated (period number). It is also possible to invert the logic (start by switching to "0" and stop by switching to "1") and to combine adjacent ports which can be alternately triggered. The last feature can be used for generating bipolar output signals in combination with a corresponding module like the PDLC glass panel driver module or the shutter driver module. In addition, two virtual ports per group, for example C8 and C9 for the C group, can be combined with other ports of the group in order to have more than one start-stop sequence per period and port. For example, the bipolar and the combination features are used for switching the PDLC glass panels. To switch the two outputs of the PDLC glass panel driver modules, the ports C0 and C1 are activated. These two ports are alternately switched every period (bipolar), starting from the first period. The two virtual ports, C8 and C9, are also activated to give an additional start/stop sequence on ports C0 and C1. The ports C8 and C9 are combined logically "OR" with ports C0 and C1. This sequence is necessary for generating the short pulse with the opposite voltage polarity which is essential for discharging the glass panels faster following the main pulse, as explained in subchapter 4.3.3. Since this pulse has to

be in the opposite direction, a one period delay is selected, which causes a main pulse on C0 to be followed by a short pulse on C1 and vice versa.



**Figure 6.4** Graphical user interface (main window)

Figure 6.4 shows the main window of the GUI. The duration of a synchronization cycle can be set in this window. This window can also display the triggering pattern of each of the 22 programmable output ports, if activated, in the upper part of the window. The different triggering parameters of a port are set in dedicated windows. For example, by clicking on the “Edit Port C ...” button, the “Port C” window is opened (Figure 6.5). The exact triggering times can be set within that window with an accuracy of 0.1 ms. After

setting all timings, a new file, which includes the assembler variables, is generated. The assembler code is then compiled before being transferred to the microcontroller.

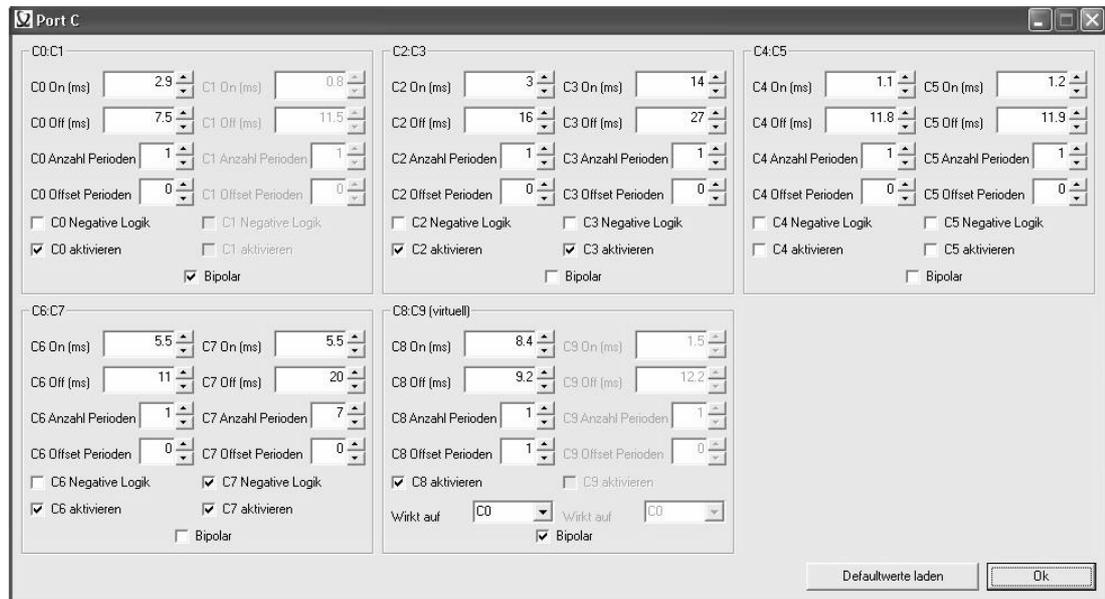


Figure 6.5 Graphical user interface ("Port C" window)

## 6.3 STARTUP AND SHUTDOWN

The startup and shutdown has to be carefully designed to minimize transient voltages and current peaks to the different components. Additional relays have been integrated in the circuit to separate power supplies and glass panels from the electronics during this switching (Figure 6.6).

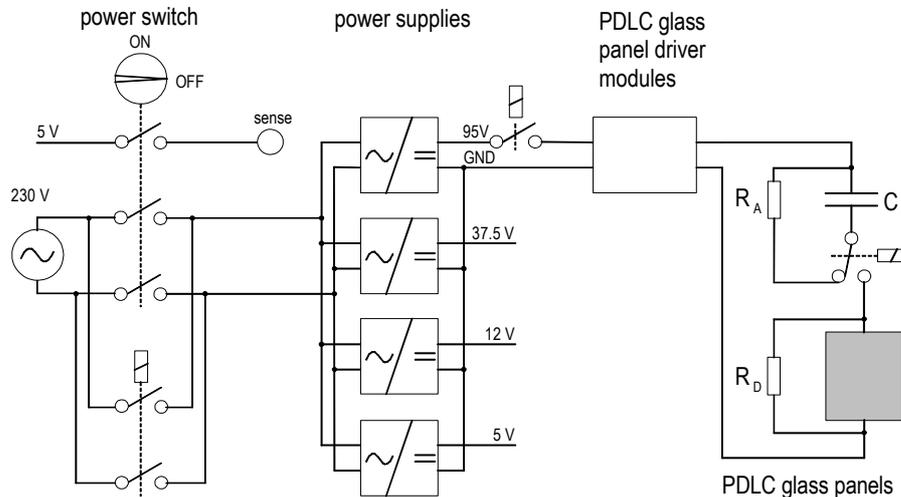
The first relay is in parallel with the main power switch, which turns on all power supplies, including the one for the microcontroller. In parallel to the main power switch, also a sense line, connected to an input of the microcontroller, is switched to 5 V. This sense line is used to tell the microcontroller if the main power switch is in the on or off state. Immediately after power up, all outputs of the microcontroller are switched to zero, except the output to activate the main relay in parallel to the main switch, which is set high. This is to guarantee that the power to the microcontroller is never switched off uncontrolled. Therefore, switching off the main power switch after this point no longer disconnects the power from the power supplies anymore because the main relay in parallel is closed. If the microcontroller detects that the main power switch is in the off state, the shutdown sequence will be started again. The main relay is only switched off by the microcontroller after all outputs have been safely switched down.

The next relay is at the output of the PDLC glass panel power supply. The microcontroller switches this relay on with a one-second delay subsequent to the main relay. This is to assure that the power supply has reached its preset output voltage before being connected to the PDLC glass panel drivers. The power supply is stabilized and maintains the preset voltage even when a load is not attached.

Nine more relays are located between the glass panels and the PDLC glass panel drivers. Each glass panel has its own relay. These relays are switched on only when the PDLC glass panels are activated. Otherwise the microcontroller switches them to the off position,

where a  $10\text{ k}\Omega$  resistor is then connected in parallel to the decoupling capacitor of each glass panel to discharge any remaining voltage.

The outputs of the microcontroller, which are connected to the data bus, are all kept at zero during the whole startup sequence. Only after all relays have been closed, are the triggering signals initiated in order to synchronize the blue-c components.



**Figure 6.6** Power up circuit

The relays are switched off in the reverse order for the shutdown sequence. The shutdown sequence is started when the main power switch is turned off. This switching is detected by the microcontroller. The microcontroller finishes the current triggering cycle and then sets all triggering outputs to zero. Next, the relays of the PDLC glass panels are opened, which is then followed a second later by the relay of the glass panel power supply. At the end the main power input relay is switched off, which thereby switches off the power supply of the microcontroller itself.

## 6.4 OPERATING OF THE SYNCHRONIZATION ELECTRONICS

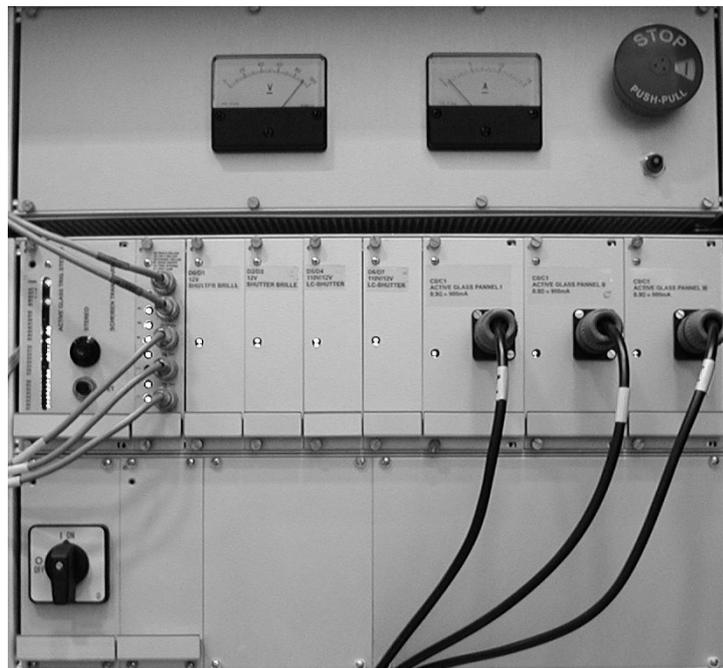
Figure 6.7 shows the synchronization electronics of blue-c. A voltage and a current gage are installed on the top side of the electronics to monitor the power supply of the PDLC glass panels. An emergency shutdown button is also integrated in the upper section of the electronics. By pushing this button, all power supplies are immediately switched off. The different modules are depicted in the diagram below. The modules, from left to right, are the frequency control module, the trigger interface module, four shutter driver modules and three PDLC glass panel driver modules. In the current version, only two of the four shutter driver modules are used.

The synchronization electronics are turned on with the main power switch, mounted on the lower left side of the electronics (Figure 6.7). The power up sequence is automatic and takes approximately three seconds to be completed. The synchronization electronics has an additional integrated switch above the main power switch for selecting the operation mode. After setting the switch, the "set" button has to be pressed in order to start the new operation mode. This switch is for selecting one of the three different operation modes. The three operation modes are described as follows:

**Stereo projection with active shuttered PDLC glass panels.** This mode is the normal operation mode and supports the full functionality of blue-c. The glass panels are actively triggered as well as all other components.

**Stereo projection without acquisition.** This mode is used when blue-c is only used for visualization. In this case, the LED illumination is not activated and the PDLC glass panels remain opaque.

**Transparent glass panels.** This mode switches the glass panels to transparent and is used for demonstration and test purposes. The synchronization electronics switches the voltage applied on the glass panels from positive to negative and vice versa without a zero volt period. The LED illumination, the cameras, as well as the shutter glasses are triggered as if it were in the normal operation mode. The FE-shutters in front of the projectors cannot be continuously switched to dark because only AC voltages are allowed.



**Figure 6.7** Synchronization electronics



## MECHANICAL CONSTRUCTION

The mechanical construction of blue-c has to fulfill the technical requirements of a collaborative spatially immersive display (CSID). On the other hand, the construction is also a visual representation of the blue-c project. The mechanical construction primarily consists of the frame for the three-sided projection room. The PDLC glass panels have to be kept in place by the construction and the different components such as tracking system, loudspeakers, IR emitters and LED illumination have to be integrated into the system. The cameras were mounted later onto a separate construction. The reason being that at the time of the implementation of the projection room, it had not yet been decided where to position the cameras. This is also the reason why the camera support structure was not integrated into the blue-c design.

The room where blue-c is installed has to be absolutely dark, so that the light does not interfere with the image acquisition and projection. Therefore, additional curtains were installed in the room.

### 7.1 ARCHITECTURAL DESIGN

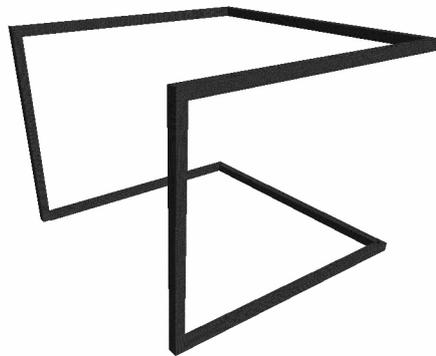
blue-c has a unique feature, which is unlike other SIDs such as the CAVE™: the switchable PDLC glass panels. This feature is a substantial element in the blue-c design. In the transparent state, the glass panels open the projection room and it is possible to look through the projection walls, from one side to the other.

Because of the electromagnetic tracking system that was used, the variety of construction materials which we could choose from was restricted to non-metallic materials. Further restrictions were also encountered because of the PDLC glass panels and the projection system that were chosen. The type of PDLC glass panels which were installed is commercially available at a maximum width of 950 mm. It was decided to use three 950 mm wide glass panels per projection side. Therefore, the projection room has quadratic dimensions of 2850 mm x 2850 mm. This is a good compromise between freedom of movement inside the projection room and the overall size of the construction including the projection system. A bigger room would require four glass panels and would therefore have three gaps per projection side, one of them in the middle of the projection. For blue-c, the PDLC glass panels B were manufactured with the PDLC film laminated

up to the polished edges of the glass panels to minimize the gaps between adjacent glass panels. The projector generates a XGA image with an aspect ratio of 4:3. The height of the projection is determined by this aspect ratio and is 2137.5 mm for a 2850 mm wide projection.

The blue-c design was created with a considerable contribution from Andrew Vande Moere from the CAAD group. In the following section, the evolution of the design is described.

**Fundamental support frame.** With projection screens made out of PDLC glass panels, it is possible to let the projection screens optically disappear with a flick of a switch. The glass panels have to be held in place by a frame construction, which should be mechanically rigid and at the same time light from an optical point of view. The glass panels are not capable of supporting any forces. It is therefore important that all mechanical forces are supported by the frame construction and kept away from the glass panels. The structure is made of fiber-reinforced composites (glass and carbon), which have a high level of rigidity. Figure 7.1 depicts a first sketch of the frame that keeps the glass panels in place. The design was inspired by a chair without the backrest. This frame only supports the glass panels on the upper and lower edges, except for the first two glass panels on the side walls, which are also supported by the two vertical beams. The idea is to reduce the support structure to a minimum and to give a full, undisturbed panoramic view when the glass panels are switched to transparent. The glass panels are placed directly one beside the other and also in the corners, where the front wall is combined with the side walls, there is glass directly beside glass. This allows a three-sided projection to be performed without shadows caused by the frame.



**Figure 7.1** Basic glass panel support frame

The structure is realized with quadratic glass fiber profiles of 100 mm cross section. The exterior size of the frame structure is approximately 3 m x 3 m x 2.3 m.

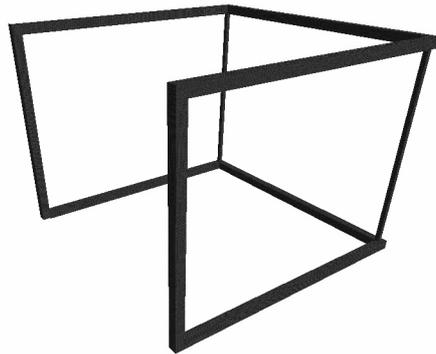
**Reinforced support frame.** Each of the nine PDLC glass panels weighs approximately 80 kg. The glass panels are mounted beside one another with a very small gap in between. Therefore, it is important that the whole construction is absolutely rigid. Two additional vertical supports had to be integrated on the back side of the construction. Carbon reinforced supports with a quadratic cross section of 50 mm were used. The supports are

placed outside, behind the corner of the back and the side walls, where they do not interfere with projection (Figure 7.2).



**Figure 7.2** Support frame with vertical reinforcement and glass panels installed

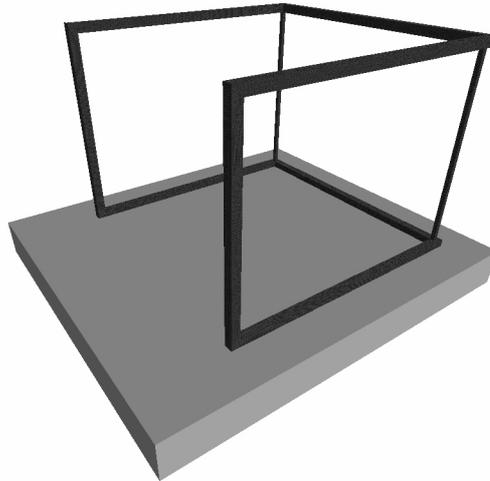
Due to the smaller cross section of the two back beams, they are less evident than the rest of the structure and do not disturb the continuity of framework and glass. Therefore, the fundamental design of the chair without the backrest could be maintained. Figure 7.3 shows the frame structure with the two additional supports on the back side.



**Figure 7.3** Glass panel support frame with reinforcement

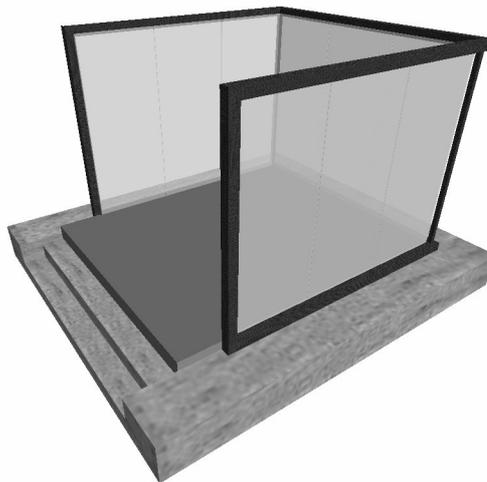
**Support frame on platform.** The platform under blue-c has both a technical and a design function. The platform is necessary for integrating the electromagnetic tracking system. In addition, it offers the possibility to integrate loudspeakers, the subwoofer and other components. The pedestal accents the frame construction and prevents the glass panels from being accidentally hit from the outside. The pedestal is made of wood to avoid eddy currents caused by the electromagnetic tracking system and to avoid distorting the emitted magnetic field. The use of natural materials is part of the design concept. Beech,

in its natural hue, is used for the platform. The wooden structure made of beech and the black beam match perfectly. Figure 7.4 shows the platform with the frame construction.



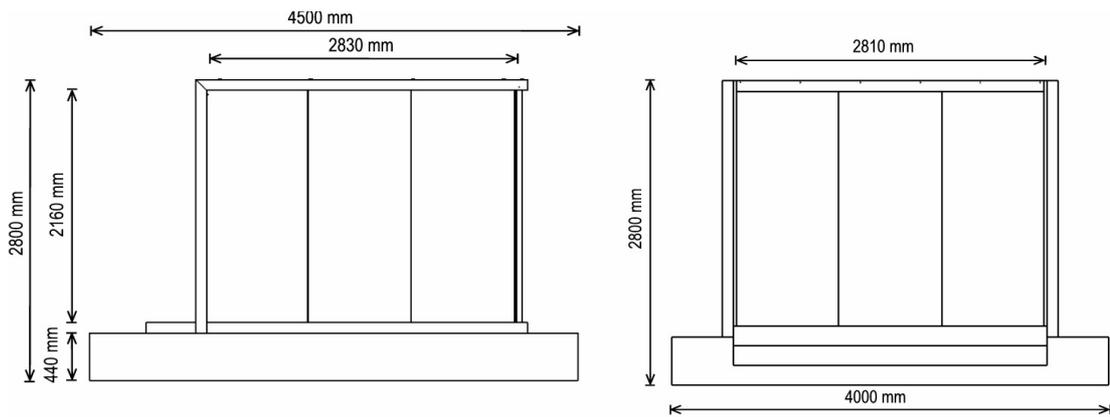
**Figure 7.4** Glass panel support frame on platform

**The final design of blue-c.** Stairs are integrated in the front side of the platform to facilitate the access to the projection room. The stairs direct the user to the entrance of blue-c and end half a meter behind the projection room. This allows the user to move around inside the projection room without worrying about falling down. The frame construction mounted on the platform uses profiles with a 100 mm cross section. Therefore, the interior of the projection room is elevated 100 mm over the platform in order to have the same height as the profiles of the frame structure. The interior floor of the projection room is covered with a blue carpet to facilitate the silhouette recognition. Figure 7.5 shows the final design of blue-c with the glass panels.



**Figure 7.5** Final design of blue-c

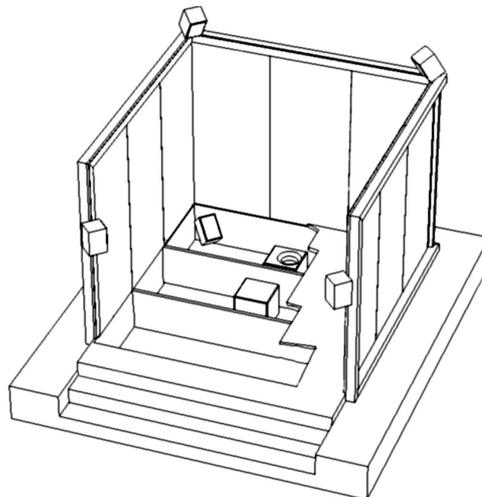
A side and a front view of the blue-c CAD model is shown in Figure 7.6.



**Figure 7.6** Side and front view of blue-c

## 7.2 COMPONENTS INTEGRATION

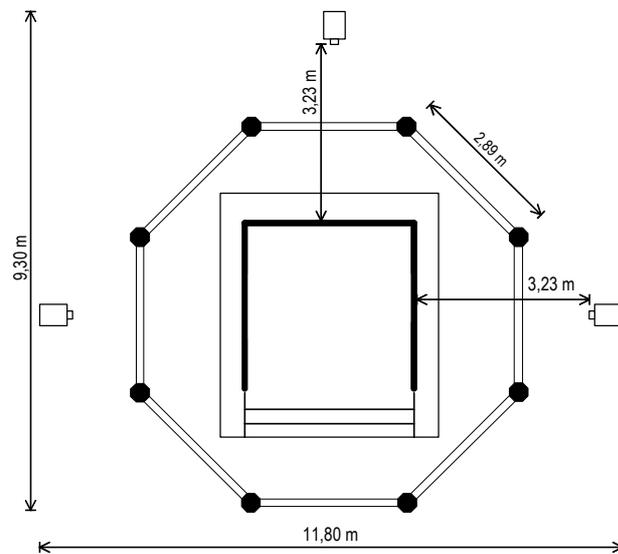
The components integrated in blue-c are a tracking system (Ascension Flock of Birds), six loudspeakers (Yamaha MSP5), one subwoofer (Yamaha SW10), the active LED illumination, IR-emitters and the PDLC glass panels. The tracking emitter is integrated in the middle of the wooden platform, thus it is not visible to the user (Figure 7.7). The two lower front loudspeakers and the subwoofer are also integrated in the platform. The floor of the platform can easily be opened to access all the integrated components. Cable channels are integrated in the beams with enough space for the cables of all the components, placed on the upper part of the construction, including the cables for the PDLC glass panels. Along with the wooden platform, there is enough space for all cables and connectors of the system. The chosen materials, wood and composite fibers, assure that the tracking system will function accurately. The cables as well as the loudspeakers, which are at a distance of 1.5 m from the emitter of the tracking system, do not have an important influence on its accuracy. The results from preliminary tests showed that the electrically switched glass panels do not interfere with the tracking system either.



**Figure 7.7** Components integration in blue-c

From the sixteen fire-wire cameras used in blue-c, eleven cameras are placed outside the blue-c projection room. A dedicated octagonal structure was built around blue-c onto which the cameras were mounted. The octagon is based on eight vertical supports (marked in black in Figure 7.8), interconnected by horizontal beams placed 3 m above the ground to facilitate the access to blue-c. The construction is based on standard aluminum profiles and offers maximum flexibility for positioning the cameras and other components. Each camera is connected via fire wire cables to one node of the Linux-cluster. The signal is amplified every five meters with a repeater. Up to three repeaters are used for each camera.

Two projectors are placed in front of each of the three projection walls. The projectors are equipped with 1.2:1 lenses which allow the projectors to project directly without the use of any mirrors to shorten the projection distance. The projectors are mounted on dedicated racks that are placed on the floor.



**Figure 7.8** Ground plan of blue-c

Figure 7.9 shows the complete blue-c including a part of the camera support structure. Two loudspeakers and part of the LED illumination are visible on the top of the blue-c

frame. The cameras outside the projection room are mounted downwards from the aluminum octagon on vertical telescopic beams.

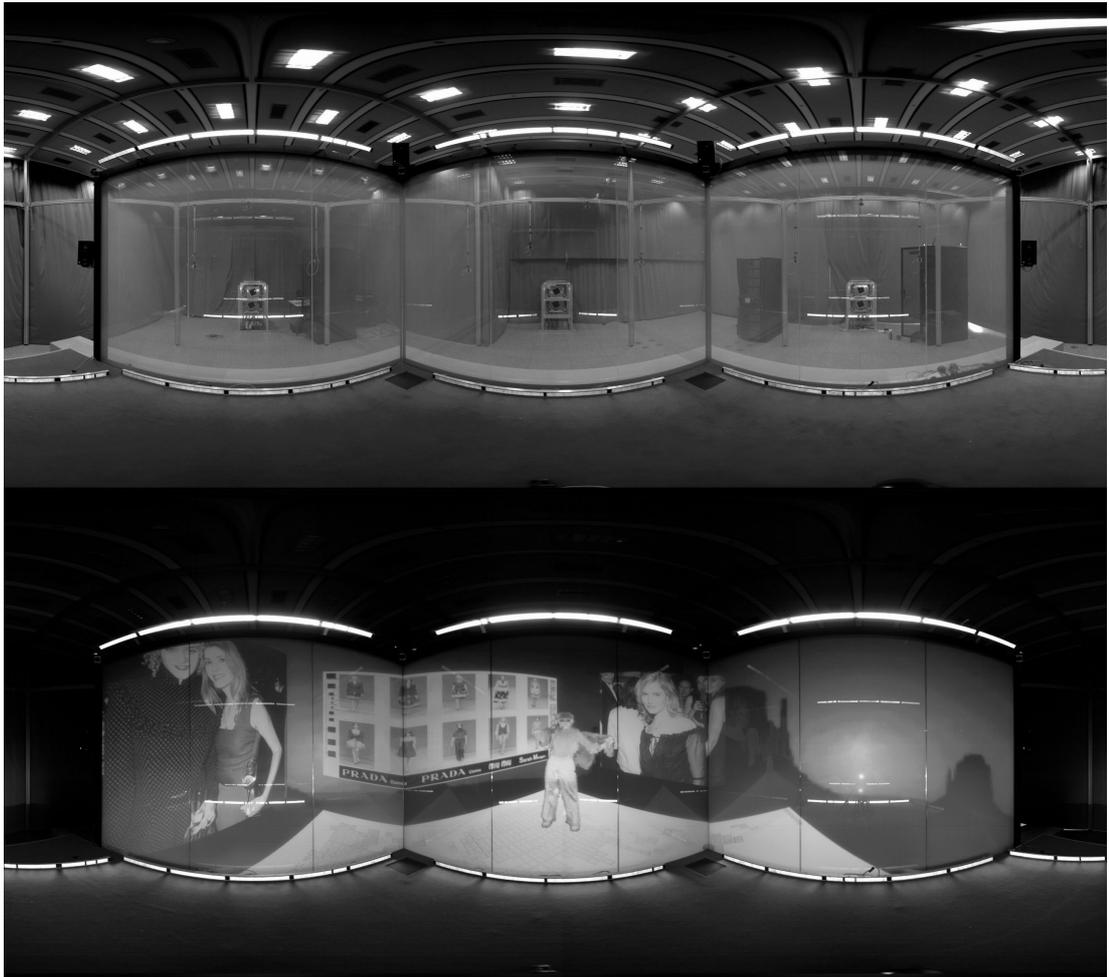


**Figure 7.9** View of blue-c and camera support structure

Two panoramic views from inside the blue-c projection room are shown in Figure 7.10. The images have been taken with a 360° panoramic camera and are therefore heavily distorted. The upper image was taken with the PDLC glass panels switched to transparent. The projection systems of all sides are visible behind the transparent glass panels. The LED clusters are visible on the upper and on the lower side of the projection walls.

The lower image in Figure 7.10 shows the panoramic view with the projection switched on. The projected application is the “IN:SHOP“ from Silke Lang, a member of the CAAD group. The LED illumination is visible above and below the projection walls.

The corners between adjacent projection sides and the gaps between the glass panels can also be seen.



**Figure 7.10** 360° panoramic images from inside blue-c

## MEASUREMENTS AND RESULTS

After finishing the construction of blue-c and integrating all components, some fine-tuning had to be performed to get the best results out of the system. The implemented triggering timings and the optical reaction of the components are described in this chapter.

### 8.1 OPTICAL RESPONSE OF COMPONENTS

The simultaneous stereo projection and image acquisition is dependant on a carefully designed sequence of events. The optical responses of the different components have to be precisely synchronized. This is done with dedicated synchronization electronics. In the following section, the triggering sequence is explained and the optical response of the components is analyzed. Due to the imperfection of the material and the components, the perfect triggering sequence does not exist. Therefore, a compromise between the quality of projection and the quality of acquisition, has to be made.

#### 8.1.1 Programmed Triggering Sequence

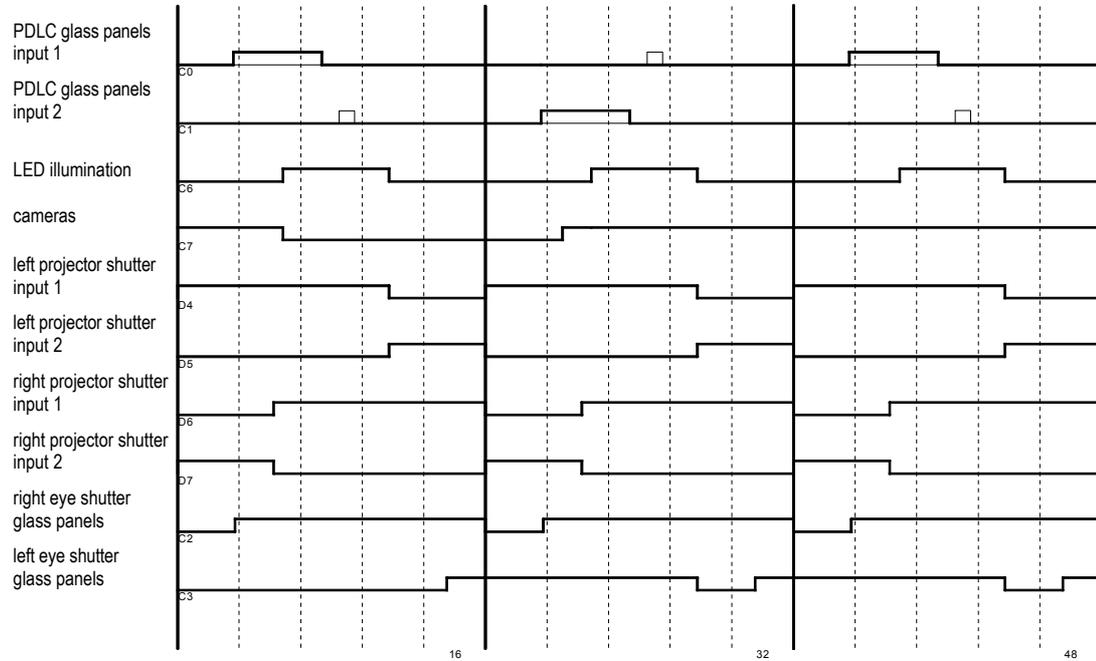
The graphical user interface (GUI) allows the exact trigger timings of all components to be easily programmed. The GUI visualizes the trigger signals in a chart, which helps the user to better understand the programmed triggering sequences. Figure 8.1 shows a chart of trigger signals with three periods. The triggering signals correspond to the signals at the output pins of the microcontroller which is in the synchronization electronics. The first two signals plotted in the chart trigger the PDLC glass panel driver modules. The two inputs of the modules are alternately triggered by long pulses in order to create a voltage output of alternating polarity, as explained in section 6.1.2. The short pulses between the long pulses are used to discharge the capacitance of the glass panels.

The next two signals trigger the LED illumination and the cameras. The LEDs are on as long as the corresponding triggering signal is high. On the other hand, the camera is only triggered by the falling edge of the signal and the camera integration time is determined by the camera itself.

Four signals are used to activate the shutters in front of the projectors. Each of the two shutter driver modules has two triggering inputs. One of the two triggering inputs is set to "high". The result is that the FE shutters, which are at the modules output, are

exclusively driven with positive and negative voltages. When input 1 is high and input 2 is low, a positive voltage is applied to the FE shutter, thereby switching it to black. Conversely, the shutter is transparent when input 1 is low and input 2 is high.

The last two triggering signals in Figure 8.1 are used to trigger the IR emitter driver via the interface module. When a signal is high, the corresponding shutter of the shutter glasses is switched to black.



**Figure 8.1** Triggering signals

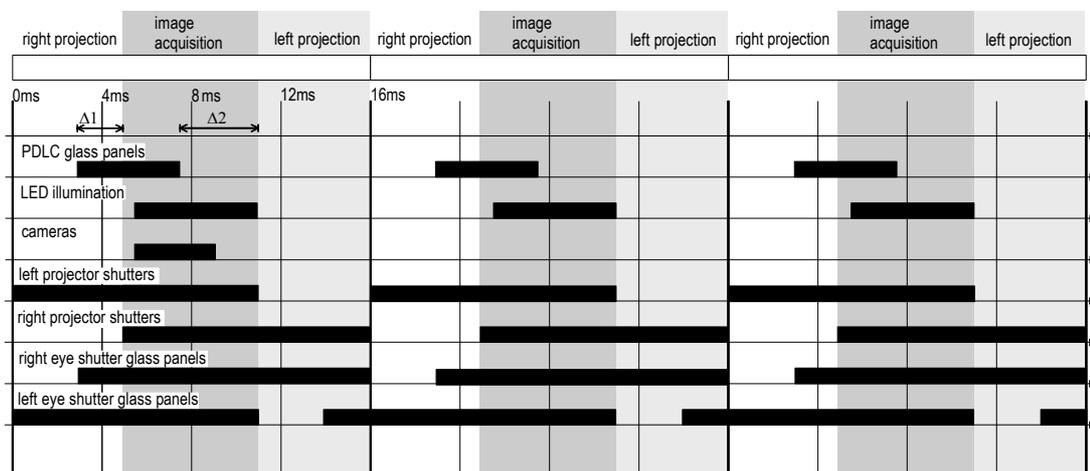
In the following section, an example is given to explain the triggering states for a specific time, as depicted in Figure 8.1. The second dotted line, which corresponds to a time of 6.4 ms. C0, is high which therefore triggers the PDLC glass panels with a positive voltage. C6 is also high, in order to activate the LED illumination. The camera is triggered with the negative edge of C7. D4 is high and D5 is low, which causes a positive voltage to be applied at the left projector shutter thus switching it to black. D6 is positive and D7 is negative, which causes the right shutter to be switched to black. C2, which is connected to the right eye shutter glass, is high thereby triggering the shutter to black and C3 is low thereby triggering the left eye shutter glass to transparent. C3 would normally be high at this point, however it is still low because it is the first cycle after the start up of the microcontroller. This status is determined by the code used in the microcontroller.

The triggering diagram in Figure 8.1 was used to extract the triggering timings displayed in Figure 8.2. These triggering timings, marked in black, show the active times of the different modules and drivers. The PDLC glass panels are transparent in the active state. The cameras and the LED illumination are on in the active state. The projector shutters and the shutters of the shutter glasses are black during the active state. Each of the three trigger cycles, shown in Figure 8.2, is further subdivided into a right projection, an image acquisition and a left projection time slot. This division has been made in correspondence to the triggering of the projector shutters.

Some components have a fast reaction time while others have considerable delays when switching. The LED illumination, the camera and the shutters in front of the projectors

all have fast reaction times. Whereas, the PDLC glass panels and the shutters of the shutter glasses have longer transition times. Therefore, the triggering of these components has to be executed earlier in order to synchronize their optical response. The triggering start of the PDLC glass panels has been anticipated at 2.1 ms ( $\Delta 1$  in Figure 8.2) in relation to the image acquisition phase. The triggering of the PDLC glass panel ends 3.5 ms ( $\Delta 2$  in Figure 8.2) before the end of the image acquisition phase. The LED illumination is on for a period of 4.5 ms. Therefore, the camera integration time can also be set up to a maximum of 4.5 ms, if desired. However, a shorter integration time is preferred in order to only have the cameras on during the most transparent phase of the glass panels. The plotted camera integration time in Figure 8.2 is 3.5 ms.

The camera triggering frequency is set to only acquire images every seventh cycle of the basic triggering frequency of 62.5 Hz. This corresponds to 8.9 images per second. This value has been chosen because it allows enough time for the acquisition system to process the incoming images. All other components are visible or partially visible for the user. Thus, they have to be triggered at the higher frequency of 62.5 Hz to avoid flickering, which would be disturbing for the user.

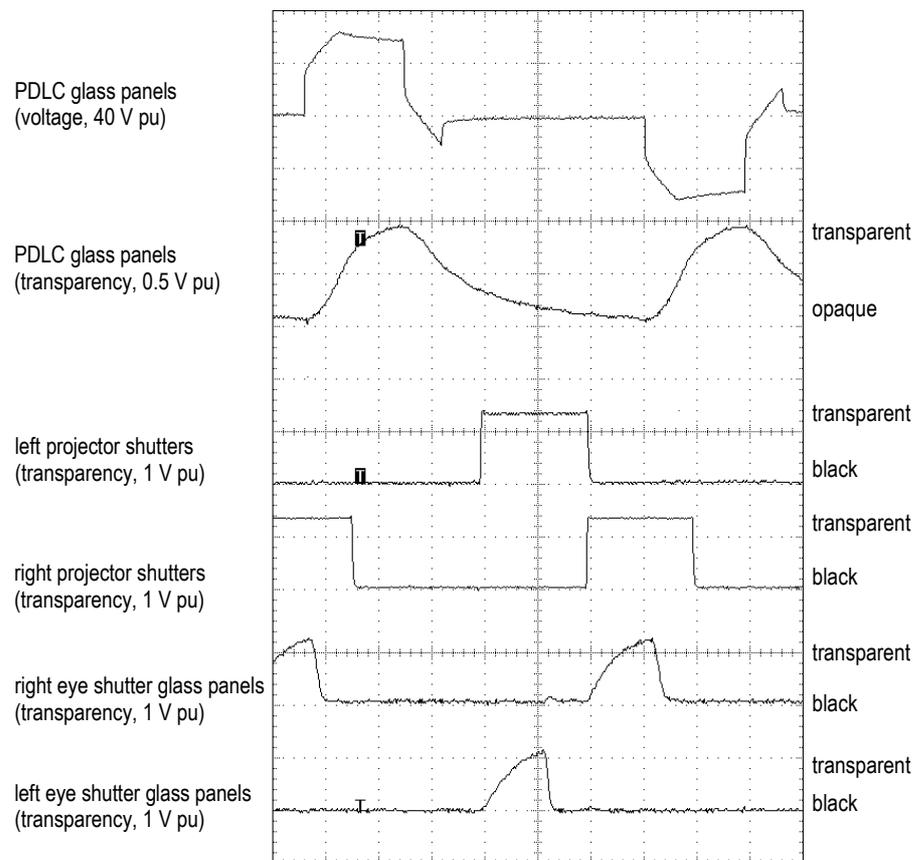


**Figure 8.2** Triggering timings

### 8.1.2 Measurements Triggering Sequence

The optical responses of the different components which are part of the triggering inputs are described in this section. The measurements have been performed in blue-c, triggered with the triggering sequence described in the previous section. All optical measurements were performed with a photo transistor in series to a resistor and a white LED. The devices to be measured were placed between the photo transistor and the LED (Figure 4.18). The output voltage of the photo transistor is high if the device is transparent and low if it is opaque. All measurements were performed with a dual-channel oscilloscope. The oscilloscope was directly triggered by the external triggering input from the synchronization electronics. This method allows the different measurements to be compared because they were taken during the same time interval as the synchronization cycle. The measurements were combined into one graph in order to display a better overview of the timings (Figure 8.3). The first measurement in the plot is the voltage measured directly on the PDLC glass panel, as described in Chapter 4. The next measurement is the optical response of the glass panel. The response delay is displayed well. The next two plots show the optical reaction of the FE shutters in front of the projectors. The reaction time is very fast for both switching directions. This is not the case

with the optical response of the LC shutters in the shutter glasses, shown in the last two measurements of Figure 8.3. The rise time is slow when changing from black to transparent, whereas the change in the reverse direction is faster but still noticeable.



**Figure 8.3** Optical response measurement

The trigger timings and the optical responses have been combined in Figure 8.4. All components start to react, with very little delay, to a change in the corresponding triggering signal. However, the rising and falling times are quite different, as previously mentioned.

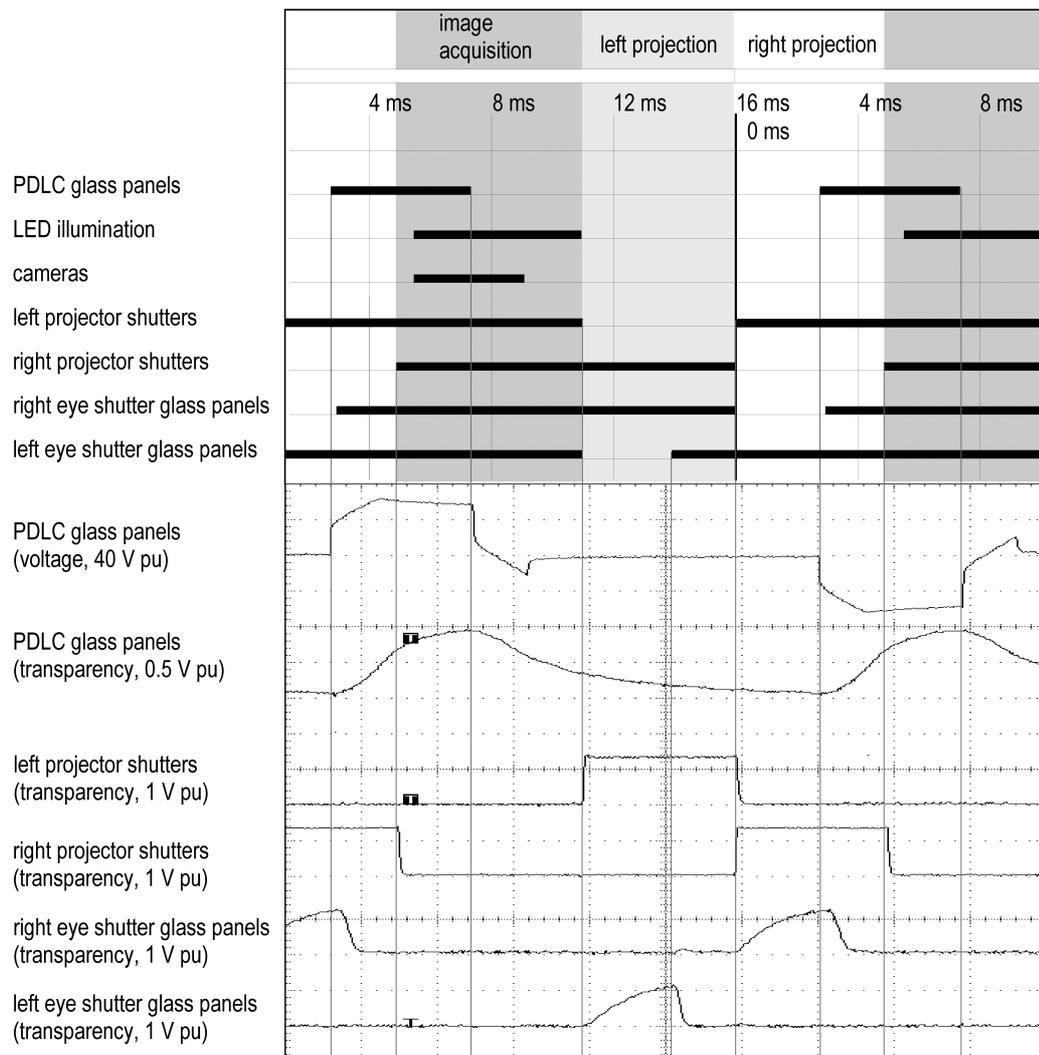
For the user wearing shutter glasses, the separation between the images of the left eye and the right eye is 100% of the shutter glasses capability. The same is true for the blanking of the LED illumination with the shutter glasses. Nevertheless, a very limited crosstalk between the two projection channels and some illumination is still visible. The reason is that the shutter glasses do not perfectly block out all light during the black state and there is still some light passing through. But the crosstalk is very limited and not perceivable under normal conditions. The LED illumination is noticeable but not disturbing and much less visible than if one were to not wear shutter glasses (Figure 5.6).

As can be seen from the optical measurements, the shutter glasses are switched to transparent only 19% of the time, compared to 45% for a normal stereo projection. Furthermore, the rising slope covers most of the active time. In practice, the perceived image is still bright enough for a surrounding projection room such as blue-c. In addition, the fact that the rising slope covers most of the active time does not give additional blur to the perceived projection. This can be explained by the fact that the shutter glasses influence the projection as well as the perceivable ambient light. The contrast ratio

between these two light sources is not related to the duration of the transparent phases of the shutter glasses. This would be quite different if the FE shutters in front of the projectors would show this optical response, fortunately they do not.

During image acquisition, the FE shutters in front of the projectors are also darkened to their maximum capability. The projection is completely blocked. Only when looking directly into the blocked projection beam, is a very confined point of light visible.

The PDLC glass panels feature the slowest optical response of the triggered components. The camera triggering has to be adjusted to maximize the transparency of the glass panels during the camera integration time. The camera integration is started shortly before the maximum transparency of the PDLC glass panels is reached and is stopped again shortly after the transparency has decreased. The triggering voltage of 65 V, in combination with the chosen triggering time, proved to be a good compromise between acquisition and projection quality. A higher voltage would increase the maximum transparency a little but would also considerably increase the switching time from transparent to opaque. To achieve a higher transparency, it is more convenient to extend the on time of the triggering signal. The increase of the switching time from transparent to opaque is related to the achieved transparency.



**Figure 8.4** Triggering timings and optical responses

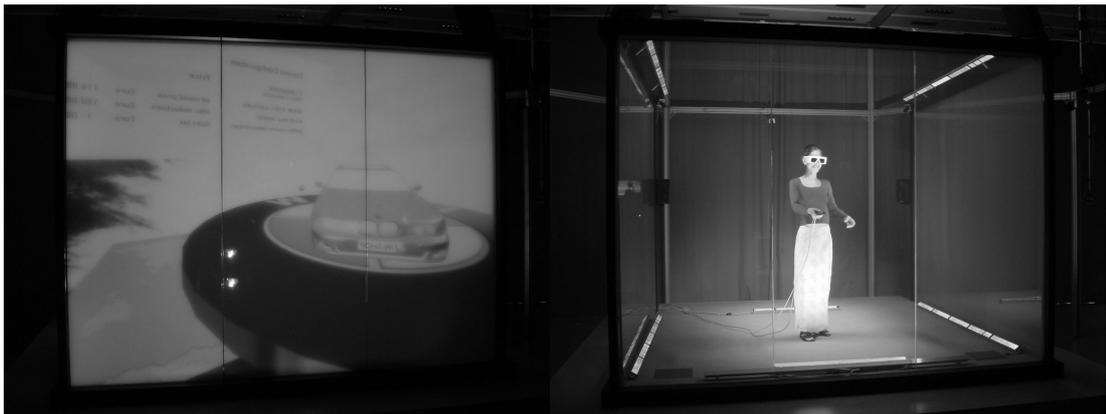
## 8.2 RESULTS OF THE SYSTEM

The projection quality is good and homogenous. A slight hot spot is visible in the projection and the gaps between the glass panels cause small, dark lines during projection. These vertical lines are visible but, because they are dark, they are not distracting. The reflections on the glass panels are more or less evident, depending on the projected images. However, they are only disturbing in scenarios where very bright objects or surfaces are displayed on one projection wall while dark images are simultaneously displayed on the other projection wall.

The transparency of the PDLC glass panels is best when looking perpendicular to the panels. This has to be taken into account when positioning the cameras.

The LED illumination shows a good level of distribution. The LEDs are oriented to illuminate the person inside the projection room with a minimum amount of scattered light directed at the glass panels. The distributed LED clusters give good light coverage except for the back side, where the LED-clusters are only installed on the floor.

Figure 8.5 shows two images taken from behind blue-c. The image on the left side was taken during the opaque state, when the projection is on. The image on the right side shows the transparent state, when the LED illumination is on and the projection is blocked.



**Figure 8.5** Projection and acquisition

Another image taken from outside blue-c, with transparent glass panels and the LED illumination triggered, is displayed on the left side of Figure 8.6. On the right side, a figure

from inside the projection room is shown with the “Infoticles“, an application from Andrew Vande Moere, running.



**Figure 8.6** Exterior and interior view of blue-c

Another interior view of blue-c is displayed in Figure 8.7. To create this image, the projection mode is switched to mono in order to avoid ghosting in the captured image.



**Figure 8.7** The “IN:SHOP“ Projected in blue-c [41]

In blue-c, the projectors are connected by VGA cables over a 13W3 to VGA adapter to the Onyx. The VGA cables have single shielding for the three colors, red, green and blue and a length of 10 m and 20 m, depending on the projector location. The signal going to the projectors is a XGA (1024 x 768) 60 Hz signal. The 10 m cable does not show any attenuation of the signal. However, the 20 m cable shows a light shadow on the right edge of dark sections projected on a light background. This shadow is very light and barely

noticeable. Independent of the cables, the three chip LCD projectors used in blue-c have a shift between the colors, red, green and blue, of up to half a pixel. This is caused by a misalignment of the three chips and is an inherent quality of most 3-chip LC-projectors.

Up to five different kinds of 13W3 to VGA or RGBHV adapters exist. In all cases the RGB signals are connected the same way, however the synchronization signals H and V unfortunately are not. Therefore the popular Sun converters, for example, will only function if sync on green is used, which is not recommended. The adapters should be checked very carefully to avoid any time-consuming signal problem troubleshooting later on.

Four two-way splitters are used for connecting the six projectors and the four monitors to the corresponding outputs of the SGI, as shown in Section 2.5. The splitters have a bandwidth of 500 MHz (3dB bandwidth). After adding the splitters, no attenuation of the signal was noticed. Some earlier tests with other splitters did not produce the same positive results. The signal was attenuated by these splitters. This additional attenuation by the splitters resulted in a projection image which was drastically darker.

### 8.3 ELECTRICAL AND OPTICAL INTERFERENCES

Interferences between components, mostly caused by electromagnetic fields, are sometimes hard to predict. In blue-c, some preliminary tests were performed to assure the compatibility between the various components.

Switching the PDLC glass panels does not interfere with any other component of blue-c, including the electromagnetic tracking system. In addition, the IR link between emitters and shutter glasses functions without problems. The LED illumination does not disturb this link. This was not the case when the strobe light was tested. The strobe light inhibits the synchronization of the shutter glasses with the IR link. Furthermore, it proved to be absolutely crucial that the shutter glasses are well shielded. An unshielded pair of shutter glasses was disturbed by the tracking system. After the shielding was restored, the shutter glasses worked again without any problems.

The shutter glasses cover the eyes very well from light coming from the front. Light coming from the side or below the user can be irritating. Therefore an optical shielding consisting of black neoprene was added to the shutter glasses to prevent light from coming in from the side or below.

## CONCLUSIONS AND OUTLOOK

This chapter summarizes the results achieved in this thesis and gives an outlook on further research directions and possible extensions of blue-c.

The blue-c system facilitates collaboration, with a high level of presence, between remote users. blue-c supports audio and visual communication and the remote user is represented three dimensionally, in full color and in actual size. The real time transfer of speech, gesture and movement allows a high level of communication. This natural way of communicating with the remote user allows both users to concentrate on the task which needs to be performed. The combination of the immersive projection system and the powerful rendering engine, which enables visualization of complex products along with the remote user, make the system an interesting platform for facilitating the product development process. The development partner and the product data can be visualized simultaneously in the same virtual room.

The "IN:SHOP" from Silke Lang displays the potential of blue-c in the field of product development. A group of people from geographically different locations can meet in one virtual room. The product, for example a car, can be visualized in full scale, along with the other meeting participants. The way of communicating with facial expressions, gesture and speech is so natural that the participants immediately start to communicate as if they were all present, standing in front of a real car. A hand movement, to point at a detail of the car becomes completely natural and can be observed by the other users. The "IN:SHOP" allows the participants to see configuration options and select between them, the selection is then immediately visualized and the car with the new configuration is displayed.

Through the realization of the blue-c project, an innovative prototype of a highly immersive projection and video acquisition virtual environment for collaborative work was built. The contribution from different fields, including computer science, electrical engineering, mechanical engineering and architecture, made the project a success.

Regarding hardware, many new concepts were integrated in the system. For the first time in virtual reality a SID was build with PDLC glass panels to enable simultaneous projection and image acquisition. The LED illumination which was used in combination with the modified shutter glasses allowed the contradicting requirements between projection and image acquisition to be fully realized. The active LCD stereo projection

enabled the image acquisition system to run independently from the rendering system. This thesis showed how the different hardware concepts were implemented in blue-c and how they were combined to create a functional system.

In Chapter 2, different concepts were presented regarding how to combine an immersive projection system with a multi-camera image acquisition system. The selected solution, with the active projection screen, offered some important advantages compared to the other systems. The advantages included the possibility to position the cameras outside of the projection room at an optimal distance from the user and the flexibility to position them as needed.

The active LED illumination in conjunction with the third phase of the shutter glasses allows full color images to be taken without disturbing the user. This is an important advantage compared to other immersive telecollaboration systems, where black and white cameras or IR cameras are often used to deal with the low light conditions.

The mechanical construction fulfills all requirements. Its stability and stiffness provides the user with a sense of confidence while using blue-c. The user never becomes uncomfortable about touching the projection walls or walking around, whereas some other VR installations do not provide the user with such security. The design of blue-c is both elegant and functional. The main features of blue-c, such as the switchable projection screens and the LED illumination, are accentuated by the design.

The six channel audio system of blue-c proved to substantially contribute to a good immersion. 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. Furthermore, at lower frequencies it can transmit vibrations to the user.

The active LCD stereo projection system shows a convincing projection quality. The high light loss compared to other systems is compensated for by the relatively low price per stereo unit and by the flexibility of being able to select the stereo projection and blanking times. This feature, in combination with the complete independence from the refresh frequency of the rendering engine and projectors, is unique and is not offered by any commercially available stereo projection system. However, the emerging DLP projectors could be a viable alternative for future installations. The primary prerequisite is that the blanking times between two images must be adapted to the image acquisition duration. In addition, the acquisition system will have to be synchronized with the projectors.

In the future, the electromagnetic tracking system should be replaced by an optical tracking system, which uses the installed cameras. A first step in this direction was already made by implementing a gesture recognition system into blue-c. An optical tracking system would make it possible to get rid of the cables, which connect the electromagnetic tracking receiver to the system.

The use of PDLC glass panels as projection screens in combination with the acquisition system is a unique feature. Switching them back and forth between the transparent and opaque state with a frequency of 62.5 Hz was a challenge. The commercially available PDLC glass panels are not optimized for fast switching. An electronic driving circuit was developed to get the maximum switching speed out of the PDLC glass panels. As a result, the switching from opaque to transparent is quite fast. The switching from transparent to opaque, on the other hand, is still slow. This transition is mainly a property of the PDLC film itself and cannot be accelerated externally. This is also the reason why the PDLC glass panels cover only 63% of their possible dynamic transparency range in the active triggered

mode. This is the bottleneck of the blue-c hardware system. Further investigations should be made regarding the PDLC film and its relaxation properties in order to optimize the switching speed.

In order to avoid the small gaps between the different glass panels, a single panel should be used per side. The problem here is that the PDLC film, which is laminated between the glass panels, is only available with a maximum width of approximately 1 m. Furthermore, glass panels of 3 m x 2.4 m would be heavy and complicated to handle. The manufacturer of the glass panels B has built the first prototypes, in which more than one film is integrated into one glass panel. In addition, the option to laminate the PDLC film between two plexiglass panels is of interest and should be considered for future installations. This material would reduce the weight of the PDLC panels, which would have a benefit on the handling of the panels as well as on the mechanical construction of the projection room.

The challenge for future installations will be to make them smaller, less complex, less expensive and more portable. Experience gained during the first blue-c project will certainly contribute to constructing a new system in the future. Fast developments in the field of projection technology, vision and computer systems, including rendering engines, will also contribute to the achievement of this goal.

The blue-c system should be tested with applications from different fields. Thus far, the tested applications have included a virtual fashion retail shop, a virtual car shop and a web access visualization. These applications have already exemplified the primary benefits of the immersive telecollaboration system. The apperceived presence of the remote participant has not been realized thus far on such a high level of quality. The integration of the remote participant into the virtual world has helped teams to collaborate more naturally and it is a big step towards reaching the communication quality of a face-to-face meeting. More extended collaborative work will have to be performed in blue-c to show the advantages and disadvantages of the system. Additional applications which make use of the blue-c functionally have to be implemented in order to exemplify the benefits of this immersive telecollaboration system. Applications in the field of product development and product design have certainly benefited from this new technology already.



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A P P E N D I X

A

DESIGN STUDIES

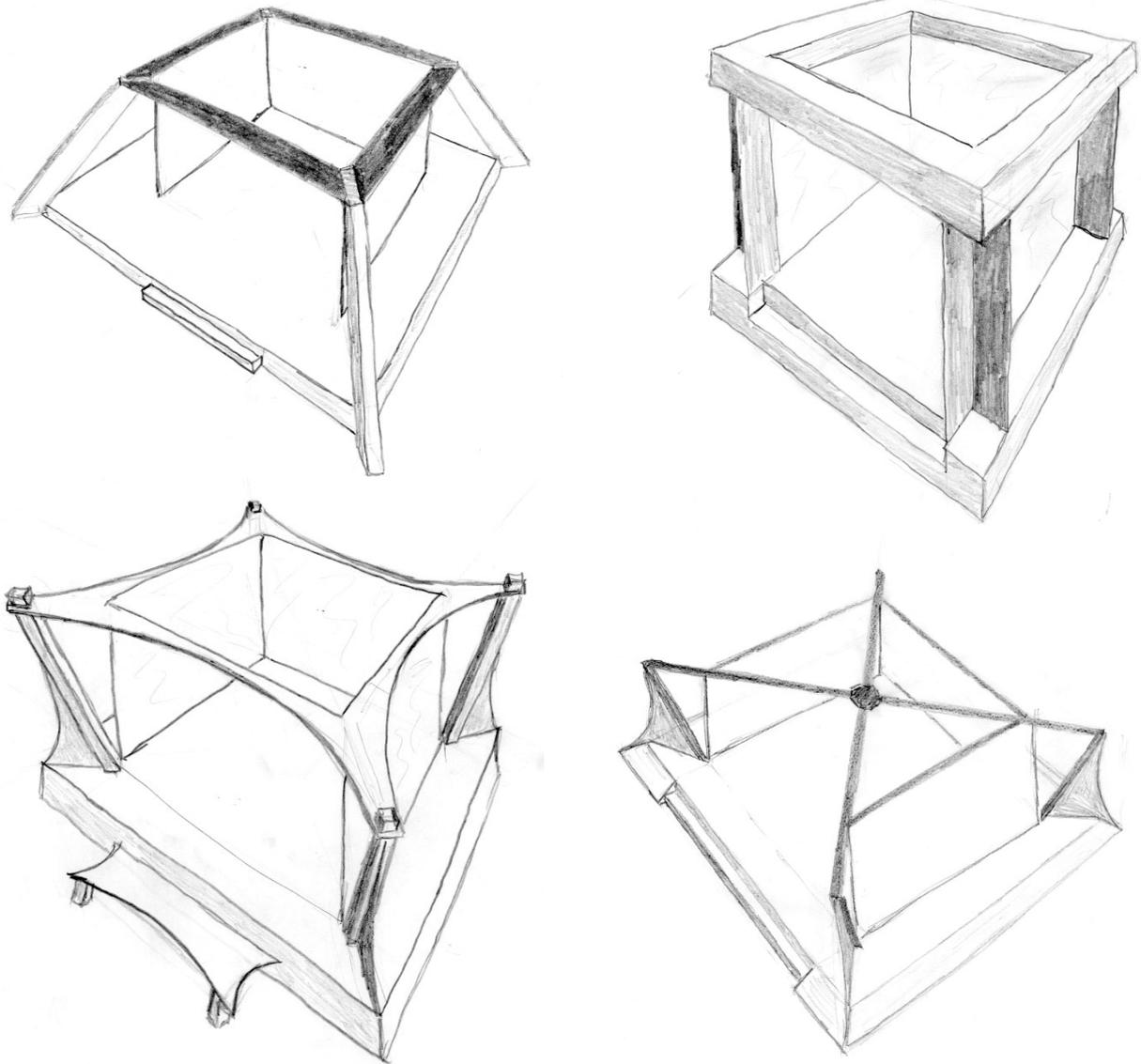


Figure A.1 Design studies

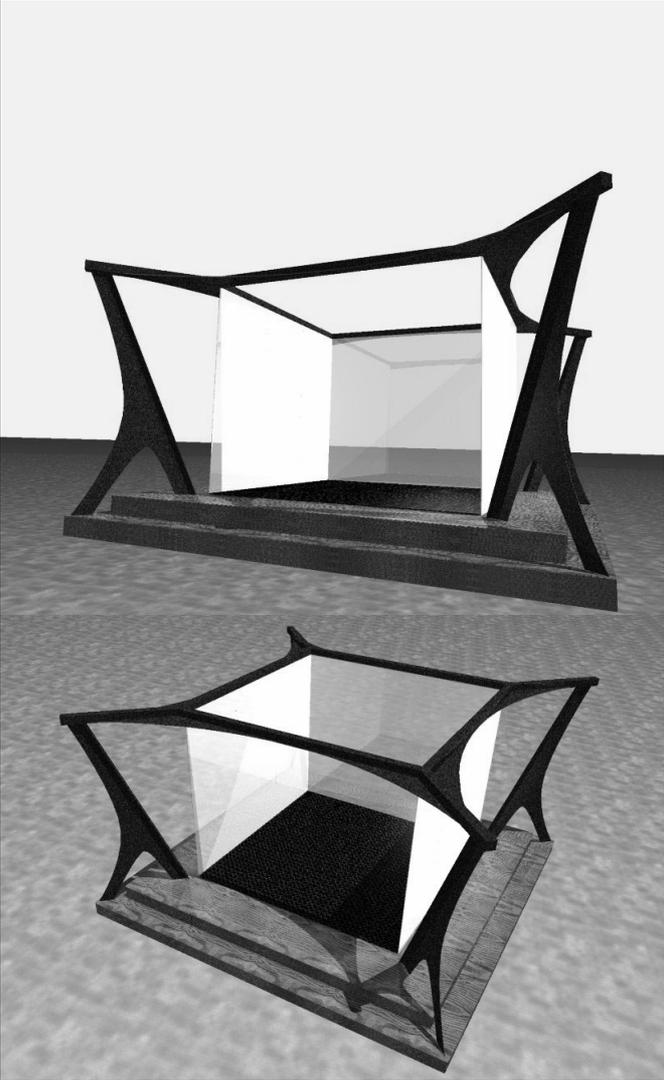
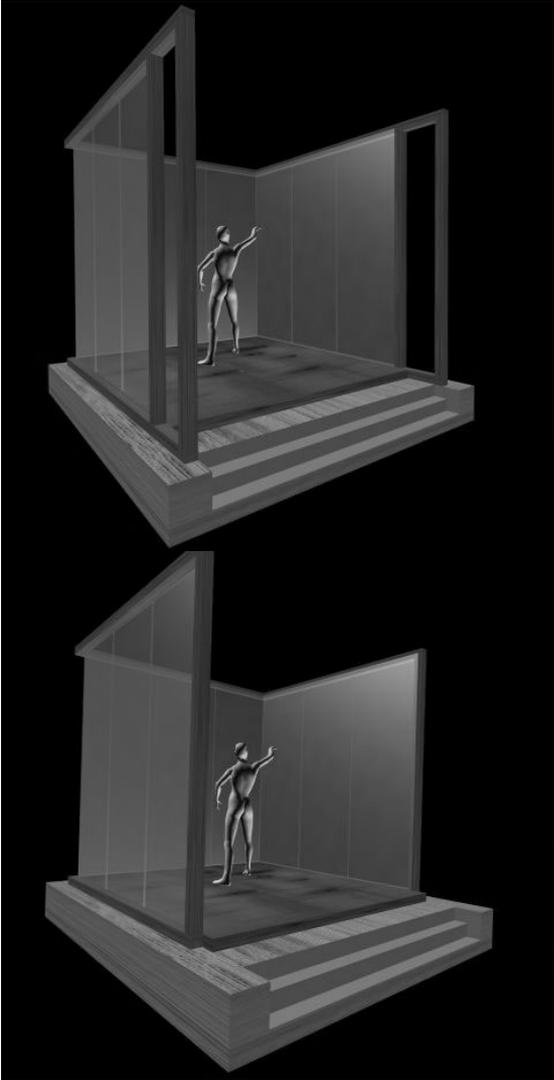
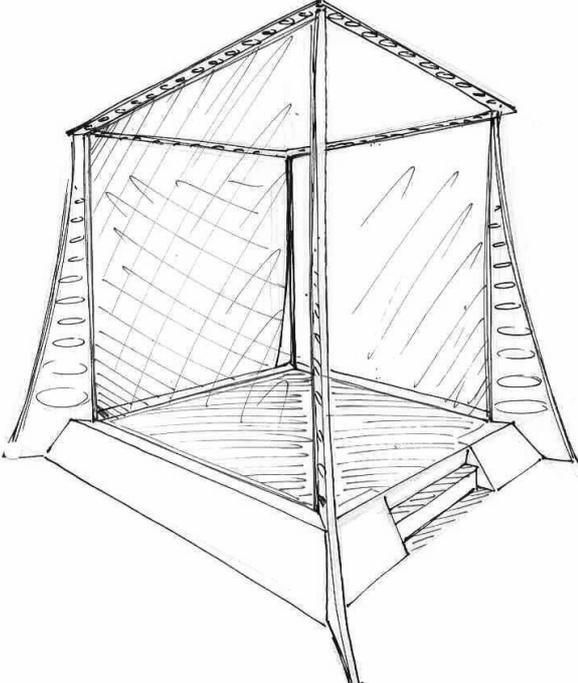
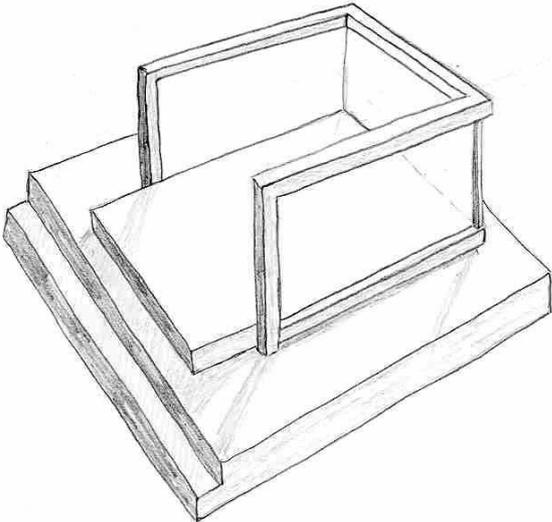


Figure A.2 Design studies

# C H A P T E R

# B

## SCHEMATICS

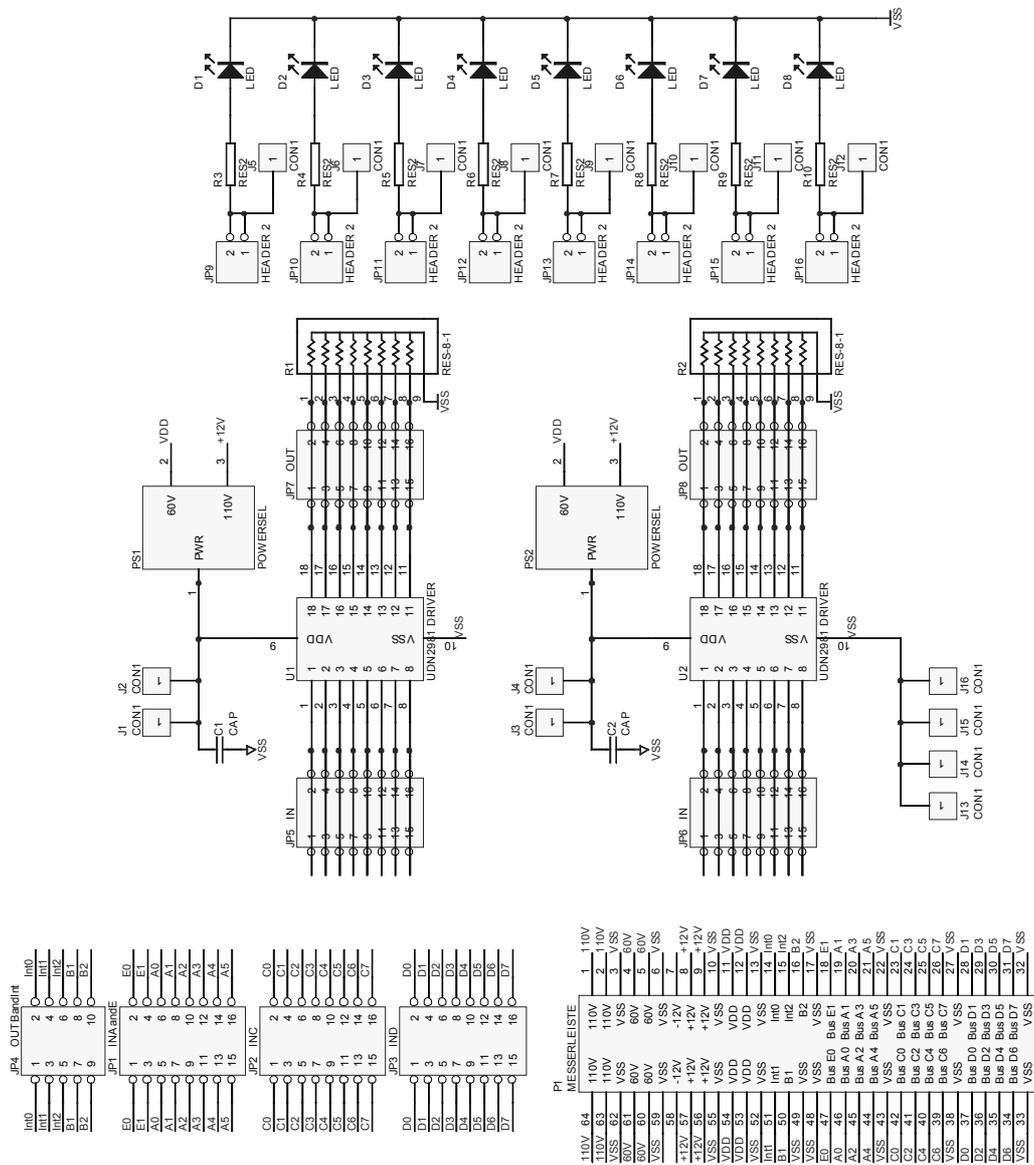
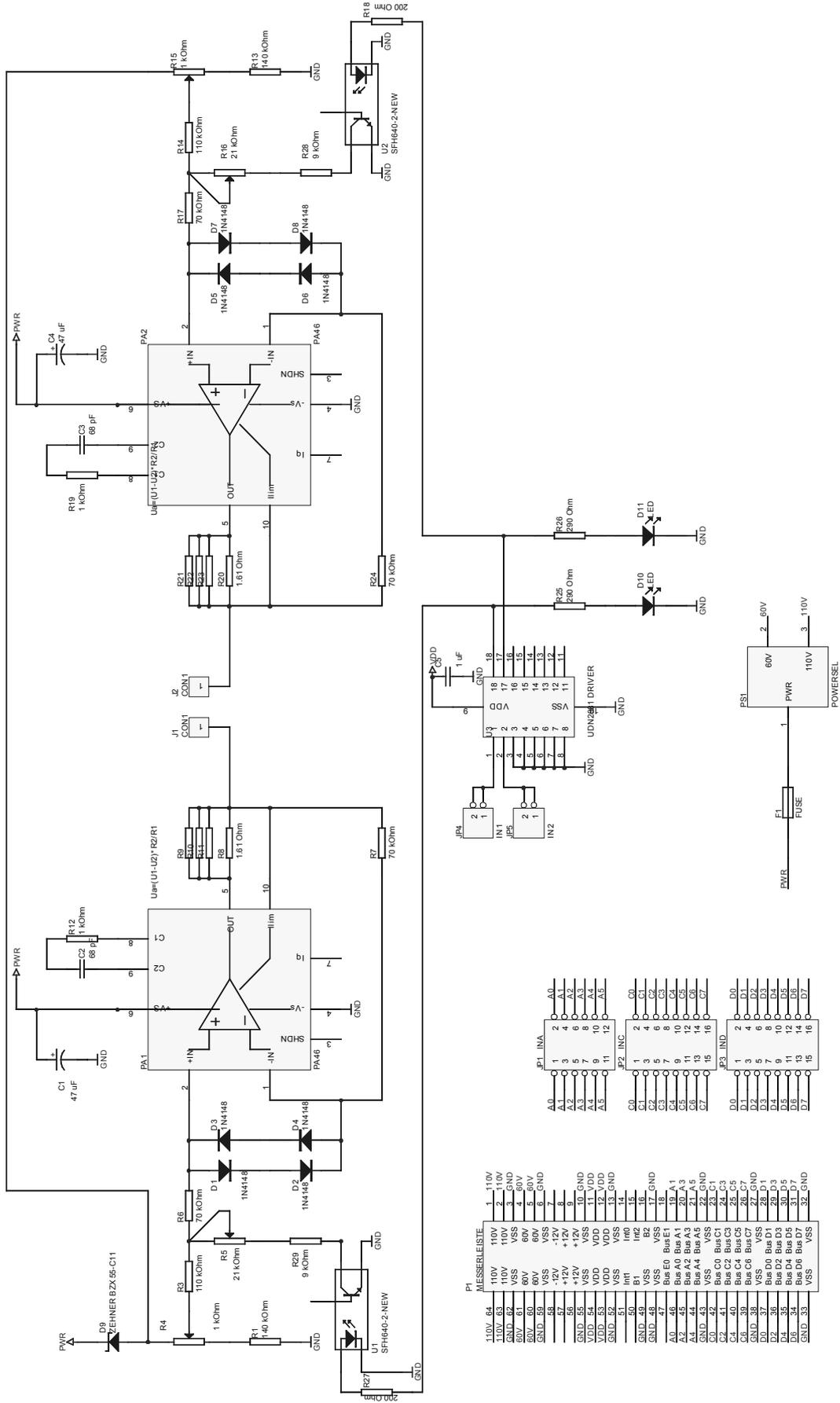


Figure B.1 Trigger interface module



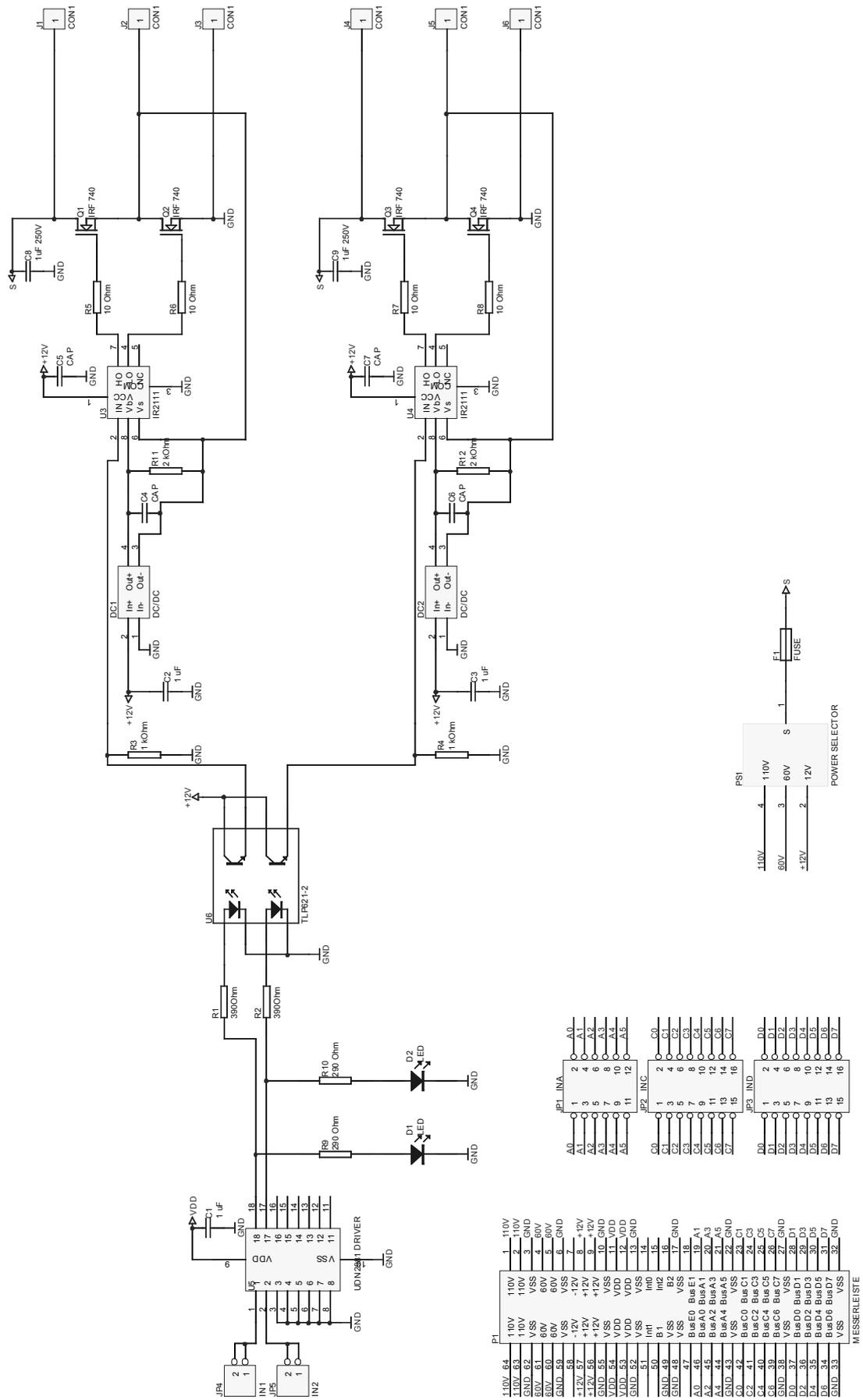


Figure B.3 Shutter driver module



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