Implementation and deployment of a stereo projection system using low-cost components

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Abstract

In this paper we present the implementation of an immersive virtual environment using a custom projective stereo display built from LCD-projectors switched by externally mounted liquid crystal (LC-)shutters. The system is basically designed to display more than one separate stereo view and therefore allows to accommodate two users simultaneously including head-tracking for independent distortion-free perception of the same scene from different viewpoints. The first development stage includes the hardware setup for only one user. Brightness is an issue and further steps to improve the system are planned. We took a closer look at the performance of the system and adapted the Quake III 3D-engine to serve as a first application.

Keywords: Active stereo projection, immersive environment, virtual reality, multi viewer display, low-cost components

1 Introduction

Currently, most immersive virtual environments are based on rather expensive stereo projection displays providing only one spatially correct virtual view to a head tracked user. Further users see the same view, but since their viewpoint is different from the tracked user their spatial perception is essentially incorrect and the view seems distorted. Such setups are therefore inappropriate for interactive 3D application, where more than one user is required to manipulate the scene. Systems suited for such requirements impose a substantial financial effort.

In this work we aim at building a multiple-user stereoscopic projection system from low-cost consumer level components. We use high brightness LCD-projectors combined with liquid crystal shutters taken from consumer shutter glasses.

The major issue for such setups is to achieve reasonable brightness, which is potentially decreasing with the rising number of users, but it is very much dependent on the technique used for stereo separation.

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The final stage should be an immersive virtual environment for multiple tracked users driven by a custom projection system without extensive use of optimizing optical elements, but the system should still offer appropriate brightness.

The rest of this section provides an overview on stereo display techniques followed by a description of the criteria for evaluation. In section 3 we present the details concerning the projector setup, controller hardware, and the augmented reality environment as well as the software tools deployed. Section 4 offers a discussion of the examined properties of the resulting setup. In section 5, we present upcoming application and ideas for improvements of the setup.

1.1 Stereo Separation Techniques

The main purpose of separation methods is to supply the user with different perspective views for left and right eye and hence create a spatial impression of a virtual scene. There are various approaches available for this task [11]. In general, they make use of some methods for coding and decoding multiple stereoscopic views within the same light field. These can be based on colour, polarisation, time, and/or spatial separation.

Time-sequential Left and right images are shown alternately on the same display surface. The viewer wears liquid crystal shutter glasses which are synchronised with the display of the left and right view on the screen so that they can only be seen by the corresponding eye of the user. The stereoscopic image quality depends on the persistence and the refresh rate of the display as well as the quality of the shutter glasses [2].

Lenticular, Parallax barrier, Parallax Illumination Basically, these techniques require displays with spatially-fixed pixels. An optical element is aligned very accurately with a pixel and produces viewing zones where only a particular group of pixels is visible when viewed from a particular direction. The system is designed so that the user's eyes are in different zones and this way a stereoscopic image can be observed without using shutter glasses. Lenticular and Parallax Barrier can be used for rear projection displays, as well.

Spatially multiplexed polarisation An optical sheet is placed on the display surface and is aligned to the pixels, which must be spatially fixed. It polarises the light emitted by adjacent pixels alternately in orthogonal states. The viewer is required to wear a pair of polarised 3D glasses to view the stereo images separated from each other.

Polarised projection In this case two polarised projection images are overlayed on the same screen (e.g. a polarisation preserving projection screen). The user wears polarised 3D glasses to view the stereoscopic image. The polarisation technique is inherently limited to separating only two views. In case of linear polarisation a view is only blocked if the light's field vector is orthogonal to the other view's. In case of circular polarisation the directions of rotation of the field vector must be opposite to each other.

Color multiplexing One approach are anaglyph images, where different colours are used to separate different views. The resulting image is perceived as monochrome. Anaglyphs are generally more straining for the eye than other methods. A quite recent approach is the Infitech system, which is based on wavelength multiplexing [9]. The two views are separated by using different wavelengths within the red, green, and blue range. The user has to wear the appropriate color filters to observe the stereoscopic image.

1.2 Evaluation criteria

Regarding quality assessments of stereo projection systems, which are also capable of supporting multiple users, the following properties have to be investigated [6]:

- Brightness: particularly essential for multi-user operation
- Crosstalk: composed of a static and a dynamic component
- Flicker: needs to be evaluated by visual inspection

Brightness is a major issue in the design of such a system. Particularly, when two or more users should be accommodated the light intensity decreases, because the time one user's stereo view is totally blocked increases. A high static transmission rate in transparent shutter state is crucial to the overall brightness of the setup.

Crosstalk describes the unintentional perception of a the other eye's view, which is strongly attenuated, but still visible. Ideally, there is no crosstalk at all in a display system. It has a negative influence on the stereo perception and is straining for the user's eyes. Two components of crosstalk can be distinguished: static and dynamic. Static crosstalk is caused by characteristic hardware deficiencies like shutter leakage in opaque state and phosphor afterglow in case of CRT displays. In the system setup we describe in this paper shutter leakage is the only source of crosstalk. Dynamic crosstalk happens during the transition phases of the LC-shutters and can be controlled by properly adjusting the signal timings.

2 Related work

An overview on the history of time-sequential shuttering methods can be found in [13]. The descriptions date back to 1924 where mechanical shuttering was implemented using spinning discs.

Approaches regarding the optimised usage of LCD-projectors with polarisation techniques can be found in [19], [16] and [10], which address the issue of light loss in such projection systems. Kunz et al. [15] used LC-shutters with customised control in combination with LCD-projectors to build a projection system with simultaneous picture acquisition to do virtual conferencing. Approaches to multi-viewer virtual environments were developed by Agrawala et al. [14] and an extension of this for use with CAVE-like environments was done by Blom et al. [12]. Fröhlich et al. [6] combined customised shuttering (mechanical and electronic) as well as polarised projection to investigate options for multi-viewer stereoscopic displays with two and more tracked users interacting within the same virtual space. Recently, a low-cost multi-wall stereoscopic projection system was presented by Miller et al. [1], which uses an approach similar to the mechanical solution by Fröhlich et al. . They use two pairs of aligned LCD projectors with shutter wheels. The wheels are initially aligned and then driven by stepper motors in a synchronised fashion. A study concerning the quality of shutter glasses and crosstalk was done by Woods in [2].

3 Setup

We took the approach of using LCD-projectors in combination with LC-shutters without exploiting any polarisation properties, which is effectively the second alternative Fröhlich et al. have chosen in their experimental setup [6].

In general, such a setup looks as shown in figure 1. The hardware per user consists of two LCD-projectors equipped with two LC-shutters and a pair of shutter glasses. The projectors are constantly generating both views, but the projector shutters are driven synchronously to the user shutter glasses so that left and right views are time-sequentially displayed and perceived by the viewer. In a two viewer environment one pair of shutter glasses goes completely opaque during the display of the other user's view.

For a single user setup it would certainly be possible to drive all the shutters by tapping into the vertical sync sig-

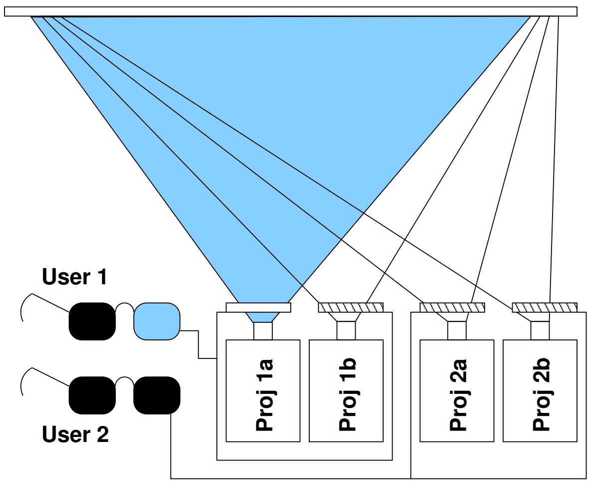


Figure 1: Basic configuration of a two user stereoscopic setup purely based on LC-shutters.

nal and use standard IR-base stations. But for two users the transparent phase needs to be halved and signals properly synchronised, which makes customised shutter control necessary.

3.1 Hardware

During this first stage of the development we set up the environment to allow for only one user but prepared everything for adding another user. In our particular case we used the following hardware for the projection setup:

Quantity	Brand/Model	Description
2	Epson EMP-74	LCD-Projectors
1	CrystalEyes CE-3	Shutter glasses
1	i-Art Eye3D	Wired shutter glasses

The two LCD-projectors provide a luminous flux of 2000 ANSI Lumens. We chose the CrystalEyes shutter glasses due to their size (about 5cm $\times$ 4cm) to be disassembled in order to provide us with the LC-shutters for switching the projector output.

The latter were installed directly in front of the projection lenses, but preserving a small gap to allow air flow between shutters and projector casing.

The shutters offer a transmittance of 32% which indicates that a fair amount of energy is absorbed by the shutters during operation. This is even increased because of the fact that at least 50% of the time the shutters are opaque (for single user operation). The possible heat problem was addressed by installing 80mm fans and a rudimentary air duct providing steady ventilation.

Figure 2 shows an image of the actually mounted devices on the projector casing.

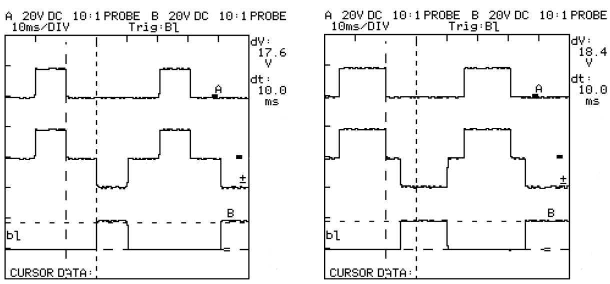
Figure 2: LC-Shutters mounted on the projector casing with cooling fan.

3.1.1 Controller unit

As mentioned above we had to build a controller unit to generate the signals for driving the LC-shutters directly.

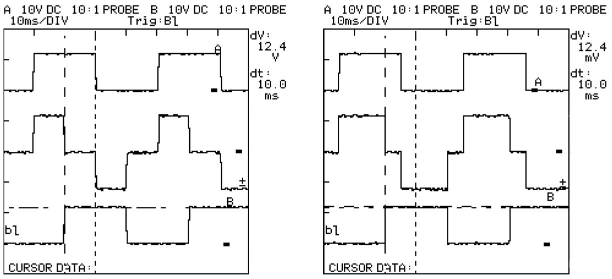
Liquid crystal elements are transparent when there is no voltage drop across the terminals and opaque when either sufficient positive or negative voltage is applied. It is crucial not to use a DC signal to drive them during opaque state, but to constantly alternate the polarity across the terminals. In figure 3 you can see the actual signal produced by the original electronics of the CrystalEyes shutter glasses. When the signal is at ± 18 Volts they are opaque. After every transparent phase the opposite polarity to the previous opaque phase is applied. For the other eye the same signal is $90°$ phase shifted.

In the case of two user operation the transparent phase for one user is halved to leave room for another pair of transparency phases. Basically there are two possible configurations: left and right view in immediate sequence (viewer sequential) and left views for all users followed by the right views (viewer interleaved). In this setup we only used viewer sequential mode since the projection hardware for the second user has not been available, yet.



(a) $\#users = 1$ (b) $\#users = 2$

Figure 3: Signals used for driving one shutter (above and below: voltage at the terminals. middle: resulting voltage drop across terminals).



(a) $\#users = 1$ (b) $\#users = 2$

Figure 4: Signals used for driving one shutter in 3-wire mode (above and below: voltage at the terminals. middle: resulting voltage drop across terminals).

The voltage levels used by the manufacturers to drive the shutter glasses were as follows:

- CrystalEyes CE-3: 18 V
- i-Art Eye3D: 12 V

One liquid crystal shutter offers two terminals. So the straight forward approach to controlling the liquid crystal is to use two wires for one shutter. We applied this one to the projector mounted parts. Alternatively, one can use only three wires to control one pair of shutters at a time. In that case two of the four terminals, one from each shutter, are connected to one wire. The remaining two are connected to separate wires. This method was applied to the user shutters, which allowed us to leave them untouched. Figure 4 shows the signals necessary for three-wire mode of operation. There the voltage level for only two terminals is shown. The third signal would be phase shifted 180° to the signal on top in both single and two-user mode.

During this first stage of the system development we use an industry standard real-time controller unit from Bernecker & Rainer Industrial Automation [5], which was made available to us at no cost to finish the first prototyping phase.

The requirements were to allow online adjustment of shutter frequency, the number of users, and the voltage levels for each pair of shutters independently. Furthermore in order to investigate the possible reduction of dynamic crosstalk we introduced a variable delay time, which lets us shift the signal transitions for the projector mounted shutters in the order of microseconds. That way it is possible to completely separate the transition phases of user and projector shutter and therefore eliminate the contribution of dynamic crosstalk.

To achieve all this, the controller unit was equipped with eight digital outputs for the shutter signals and two analog outputs for setting the voltage levels. The digital outputs are connected to an output buffer stage which translates the signals to the desired voltage level given by the analog outputs. Since the voltage range of the analog outputs only reaches +10 Volts maximum an additional amplifier maps the range to a maximum of 24 Volts.

The controller unit is also backed by a broad software layer, which allowed for easy online interaction with the controller hardware using a custom PC application.

Figure 5 shows a schematic of the actual setup.

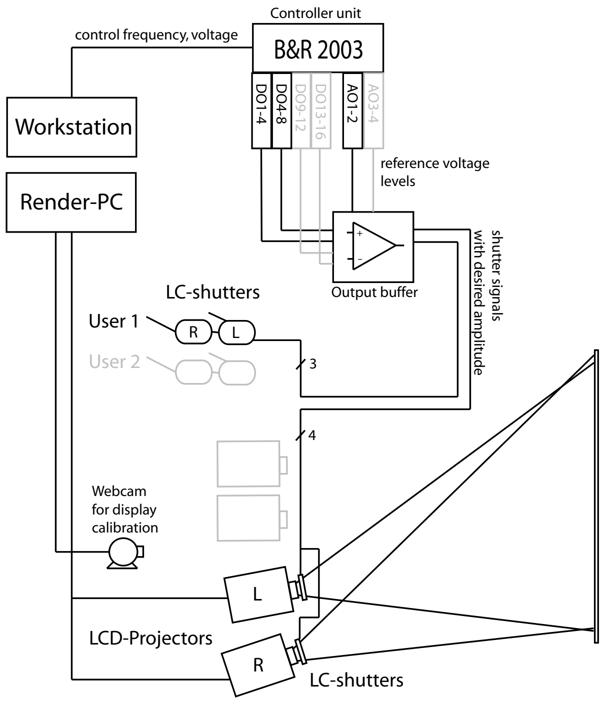


Figure 5: Schematic of the complete setup. The second user setup has not been installed yet and is greyed out.

3.1.2 AR environment

To implement the head-tracking we used Ascension's Flock of Birds (FoB) attached to the user shutter glasses. This implies the user is cable-connected to one FoB transmitting device, which does not introduce another disadvantage since the shutter glasses are already wired.

3.2 Software

As the illustration in figure 5 suggests, the projectors were not aligned to the wall, but projecting at an oblique angle. To deal with that we used the StubeRenA software [8], which is a supplement to the Studierstube augmented reality framework [7] and was originally designed to build seamless tiled displays on planar surfaces with fast registration using a webcam. It provided us with the necessary warping matrices for displaying undistorted views of a scene as well as alpha masks to clip the distorted quadrilaterals to a rectangular area. This tool was originally based on the work by Raskar et al. in [17].

We also used the Studierstube framework itself to provide us with test applications for the projection setup. The OpenTracker tracking framework was chosen to deliver the input data regarding head-tracking and alternative input devices for viewpoint manipulation.

With that as a basis we took the Quake III 3D engine and adapted it to utilise the projection setup. Whereas Studierstube is readily equipped to incorporate warping matrices and alpha masks, the Quake engine had to be extended to do so. It does support basic stereo rendering out of the box exploiting quadbuffering capabilities of the hardware, but does not calculate correct skewed viewing frusta and does not offer any means for viewpoint manipulation as needed by the AR setup. The latter problem was solved by integrating OpenTracker into the engine. This immediately enables the usage of a wide range of input devices for manipulating the world position of the player, as well.

For render hardware that does not support quadbuffering we additionally modified the engine to offer a split-screen stereo mode making sure not to affect the game engine but the rendering engine only. This should keep it still possible to play various Q3 mods using the modified engine.

4 Results

The main focus of our investigations was placed on the properties of the projection system regarding brightness, crosstalk, and flicker. That involved measurements of the LC-shutter's transmission rates including transmission vs. time response in terms of relative irradiance. Those measurements were compared to the results of the evaluation regarding the subjective perception of brightness, crosstalk, and flicker.

What we expected was an increased level of crosstalk contributed during the transition phases when switching views. Furthermore noticeable flicker was expected caused by the vertical blank due to the asynchronous operation of shutters and projectors, and the loss of brightness should be quite significant for multi-user modes.

Measurements In the setup to carry out the transmission vs. time measurements we used a simple BPW43 photo diode in combination with an Intralux DC1100 cold halogen light source [4]. The irradiance was measured using a scopemeter attached to the output of a simple I-U-conversion circuit. The measurements were done for the CrystalEyes shutters and the i-Art Eye3D for single and two-user mode over a frequency range of 60Hz to 240Hz and a voltage amplitude ranging 10 to 24 Volts. The two-user mode effectively yields transparent phases equivalent to those in one-user mode but at twice the shuttering frequency. The state transitions of the shutters were set to be synchronous, which means one view is shut exactly when the other starts to open.

The static transmission rates for both shutter types are shown in figure 6. The relative transmission rate is about 32% in either case when shutters are transparent, which confirms the manufacturer's specifications. During operation at 60Hz both models reach 28% transmission rate in transparent state and in 5% opaque state. This shows that the shutters actually do not fully reach 32% during the transparent phase.

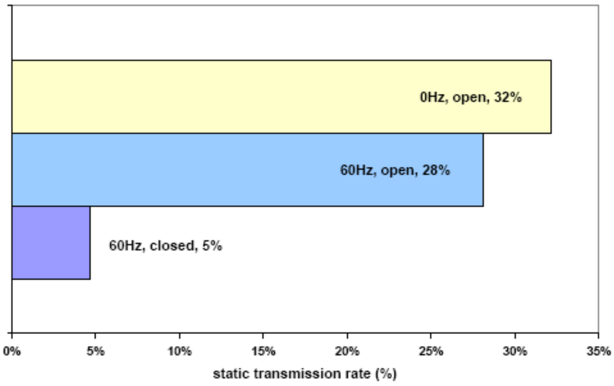
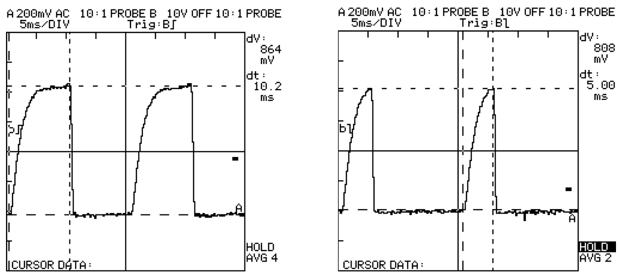


Figure 6: Static transmission at $f = 0$Hz and $f = 60$Hz.

Figure 7(a) shows the raw transmission vs. time response of the CrystalEyes shutters at 50Hz in single user mode and two-user mode (the length of the transparent phase is equivalent to 100Hz single user in the latter case). The left marker denotes the moment when the driving signal goes low and the shutter changes to transparent. The second marker denotes the low to high transition after which the shutter turns opaque. Opening the LC-shutter takes about 4ms ($\tau = 1.76ms$), which is significantly longer than closing them, where the transmission rate falls to 10% in about 185μs at a voltage level of 18 Volts.



(a) $f = 50$Hz (b) $f = 100$Hz

Figure 7: Transmission vs. time response of the liquid crystal shutters.

The shape of the shutter response during the transparent phase at 100Hz is quite similar to the one at 50Hz, but cut off at a quarter the cycle time. This suggested a gradual decrease of the maximum transmission rate with rising frequency and it was confirmed in our experiment. In figure 8 and 9 the results of the measurements concerning transmission rate as well as rise and fall time are shown. The time constant of the relaxation process during the transparent phase stays the same over the whole frequency range for both shutter models. For the CrystalEyes we measured 1.65ms and for the i-Art Eye3D 1.8ms. At 120Hz the length of the transparency phase is already below 2τ and the transmission rate therefore already falls below 27%. At higher frequencies the transmission rate decreases even further. Starting at about 28% at 60Hz for both shutter models the rate decreases for the CrystalEyes to 24% at 240Hz single user and 16% two-user and for the i-Art Eye3D to 20% at 240Hz single user and 12% two-user. The transmission rate in opaque state is constant at 5% over the whole frequency range. The voltage level has no influence on either transmission rate or rise time. The fall time then again is affected by both. The voltage level has the greatest influence on the trailing edge of the signal. From 10 Volts to 24 Volts the fall time decreases by 75% from 500μs to 110μs at 60Hz. With rising frequency the fall time decreases as well, but only between 50% at 10 Volts and 30% at 24 Volts.

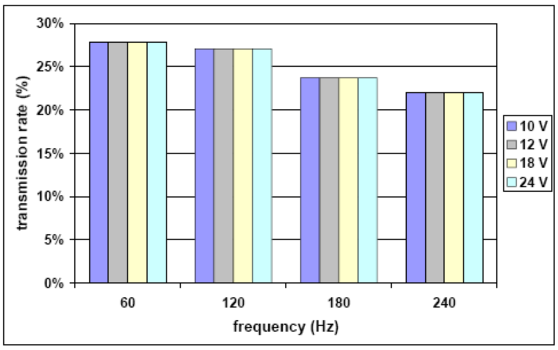


Figure 8: Maximum transmission rate at different frequencies and voltages (both shutter models).

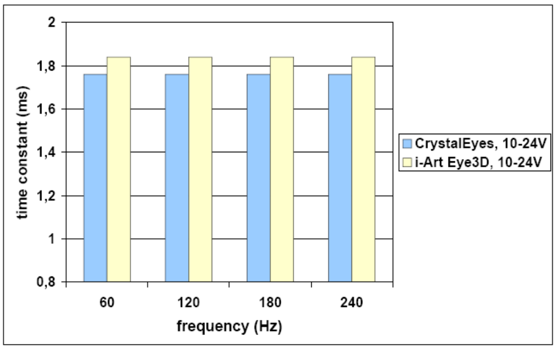
The very short time for closing the shutters compared to the rather slow response for opening them suggests that dynamic crosstalk is negligible and crosstalk was indeed not influenced by further adjustments of the signal edges. The static component is the only contributor to crosstalk caused by the insufficient opacity of the shutters in closed state. The transmissibility in opaque state also leads to an increased perceived brightness of the ghost image when the overall brightness of the displayed content is low. The decreasing transmission rate with rising frequency implies that a good trade-off has to be found between flicker at low frequencies and diminished brightness at high shutter frequency.

Visual assessment During the visual inspection of the system we investigated the perceived crosstalk, brightness, and flicker at different frequencies and voltages.

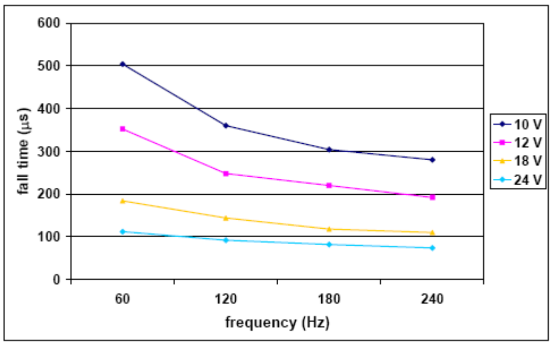
As expected the crosstalk is very low but existent and we observed no perceivable change by varying voltage or frequency except that the ghost image seems brighter when the view is getting darker at higher frequencies.

Table 1 and 2 show the results concerning perceived flicker and brightness. For single and two-user mode below 40Hz flicker is very strong. At 50Hz the projection can already be watched conveniently. At 60Hz flicker is near to non existent in either user mode, but in two-user mode the system exhibits slow pumping, i.e. variations in brightness, which should occur due to vertical blank and asynchronous operation. Above 60Hz flicker is basically eliminated but slow to very fast pumping appears occasionally when the frequency is close to some multiple of the LCD's frame rate of 60Hz. For single user mode the picture is noticeably getting a little darker at about 150Hz. Above 150Hz brightness gradually decreases further. In two-user mode the amount of transmitted light is inherently cut by 50%. Subjectively the brightness at 70Hz in two-user mode is about the same as in single user mode at 200Hz, which is quite dark already. Above 70Hz brightness is gradually decreasing, as well. The voltage level did not have any influence.

Using this hardware configuration at hand it does not seem recommendable to go beyond 70Hz for both user modes. Frequencies between 50Hz and 70Hz seem to be a good tradeoff between flicker and brightness. In two-user mode the overall brightness is a little low in general. This is where the intensity reduction of at least 72% two times on the light's way between projector and user gets really noticeable.



(a) Time constant of opaque-to-transparent transition (CrystalEyes, i-Art Eye3D)



(b) Fall time of transparent-to-opaque transition (practically the same for both shutter models)

Figure 9: Time constant and fall time at different frequencies and voltages.

#users = 1			
f	flicker	pumping	brightness
30	strong	-	
40	noticeable	-	
50	convenient	-	
60	-	-	
70	-	-	
90	-	slow	
120	-	fast	
150	-	-	little darker
180	-	slow	little darker
200	-	fast	little darker
210	-	fast	darker
240	-	minimal	very dark
300	-	-	very dark

Table 1: Perceived flicker, pumping, and brightness in single user mode.

#users = 2			
f	flicker	pumping	brightness
30	strong	-	little dark
40	noticeable	-	little dark
50	very little	-	little dark
60	-	slow	little dark
70	-	fast/little	little dark
90	-	slow/strong	darker
120	-	fast	darker
150	-	-	very dark
180	-	slow/strong	very dark
200	-	minimal	very very dark

Table 2: Perceived flicker, pumping, and brightness in two-user mode.

In this situation it is particularly unfortunate that with LC-shutters only it is impossible to exploit the inherent light polarisation of the LCD-projectors. They are actually emitting polarised light where red and blue are vertically polarised and green is horizontally polarised (named Type 1 projectors by Woods in [10]). The LC-shutters, which are basically a liquid crystal embedded between two linear polarisers, therefore had to be positioned at an angle of 45° relative to both red/blue and green. This leads to a theoretical transmission rate of 50% for the shutter glasses and the measured transmission rate of 32% of our shutter glasses, which is a common value for polarising filters [16].

Figure 10 summarises to total loss of intensity along the light path, but without considering the projection screen's influence.

Application As a first application for this setup we prepared Quake III Arena to utilise the stereo projection system. Crosstalk was no issue at all while playing the game (at $f = 50, 60, 70$Hz) and the stereoscopic image could be watched conveniently. In two-user mode brightness is getting low. Switching to $f = 35$Hz improves brightness to a certain extent. Below 35Hz flicker is unacceptable. Figure 11 shows a picture of the projection screen with a stereo view from a live Quake III test run.

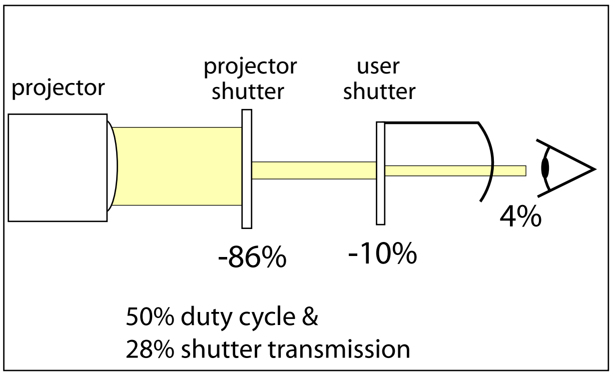


Figure 10: Intensity losses along the light path for a single user setup (50% duty cycle). The influence of the projection screen is not taken into account here.

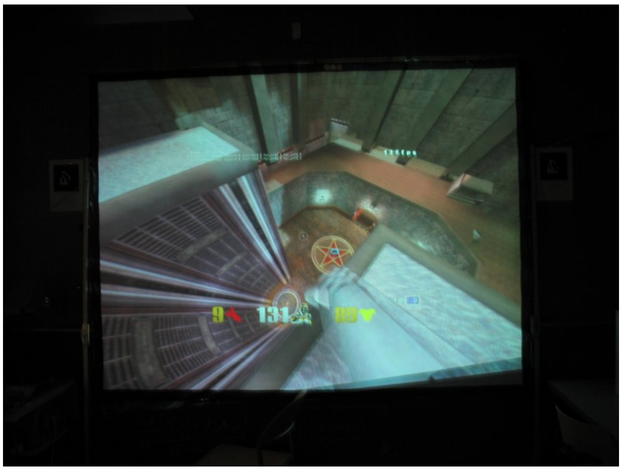


Figure 11: Picture of the projection screen taken during a Quake III Arena test run.

5 Conclusions and future work

The project demonstrates that building a running stereo projection system from consumer level electronic parts is possible and can be accomplished within reasonable time and with reasonable financial effort. The single user setup offers reasonable quality and brightness in environments where ambient illumination can be minimised to proper levels, which should be the case for dedicated laboratory rooms.

The results of Fröhlich et al. [6] can be acknowledged regarding brightness in a purely shutter-based projection environment for two and more users. Brightness is becoming an issue.

A substantial improvement to the situation should be achievable by introducing a color selective half-wave retarder between lenses and shutters, which rotates the green component by 90°. After that all three components are polarised in the same direction yielding an increased transmission rate through the first pair of shutters [16, 10].

Another possibility would be moving to passive stereo with polarised filters and correspondingly polarised glasses, which would also require a polarisation preserving projection screen and therefore boost the total costs.

To minimise crosstalk the directional dependency of the transmission rate of the LC-shutters in opaque state should also be taken into account more specifically. As far as observed the leakage is distributed non-uniformly across the shutter plane.

Regarding further development of the environment we plan to integrate the Swopper™[3] as introduced by Beckhaus et al. [18]. This basically is an ergonomic stool designed for work in office environments and can be tilted as well as rotated while sitting on it. We are going to evaluate the input interface (also as a novel means of motion control in Quake III Arena).

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