Implementing Multi-Viewer Time-Sequential Stereo Displays Based on Shuttered LCD Projectors

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Abstract

This paper reports on the implementation of a multi-user active stereo system based on shuttered LCD projectors. We have successfully implemented shuttering of four projectors to support two individual users with perspective correct stereo views. Our users did not perceive flicker above a refresh rate of 200Hz. Further timing experiments indicate that this approach should also support three or potentially four users.

1. Introduction

Providing multiple tracked users with individual stereoscopic images has always been a major challenge for projection-based virtual environments. Recently shuttering a pair of LCD projectors to achieve an active stereo display has become increasingly popular. A natural extension of this work is the support of multiple users with individual stereoscopic images by changing the timing on the shutter mechanisms. This extension was already suggested in Karri Palovuori's patent applications [15,16].

There are two main approaches for shuttering LCD-based projectors: mechanical shutters and liquid crystal (LC) shutters. Mechanical shutters are in the simplest form based on a spinning disc, which is half transparent and half opaque. [6,7,15,16] suggest this approach, which also seems to be used in a commercial product [5]. Liquid crystal shutters are widely used for shutter glasses and they were also used for shuttering projectors[10,11,12].

We have investigated the use of the shuttering approach to support two or more users. Our implementation of the LC shuttering approach for four projectors (Figure 1) worked well for two users above 200Hz – 50 images per second per eye per user. Further timing experiments indicate that this approach should scale beyond two users, but requires faster shutters than the standard LC elements we used. In addition, we have also experimented with the mechanical shuttering approach for two users, which uses four projectors and a spinning disc. This approach provides less crosstalk and more brightness than the LC-shutter based approach, but the fast spinning wheel introduces noise and vibrations, which are hard to eliminate completely.

Figure 1: Four shuttered LCD projectors. Small shutters are mounted in front of each projector.

Our main contribution is the actual implementation of a multi-user active stereo display based on shuttered LCD projectors. Our experiments show that two users can be easily supported by such systems. The mechanical shuttering delivers higher brightness and less cross talk, but does not extend as easily to more than two users because of the required rotation speed and size of the disc. Standard LC shutters have a limited switching rate and therefore support only a maximum of two to three users – depending on the actual LC shutters used. The main limitation of the shuttering approach is the reduction of brightness, which is split up across all eyes and users. High brightness LCD projectors are readily available, which ameliorate this limitation. Our experiments confirm that shuttering LCD projectors provides a feasible mean to support a small number of users in projection-based virtual environments.

2. Related Work

Shuttering devices for time-sequential stereoscopic displays have a long history. Lipton provides an overview in [13]. Interesting in this context is Lipton's reference to Hammond's work on the Teleview system from 1924 and 1928. Hammond used a spinning disc and two projectors to generate a field-sequential active stereo image. He also used a synchronized spinning disc in front of the user's eyes to provide each eye with the corresponding image. Palovuori's patent application from 2001 [15] presents basically the same approach based on the spinning disc and shows nearly identical images. In addition Palovuori suggests the use of LC shutters in front of the users' eyes and/or in front of the projectors. Palovuori's patents also mention the extension of the shuttering approach to more than two projectors, which he calls multichannel images. In [16] Palovuori suggests the development of pulsed projectors, which emit bright images only during their active cycle. They are dimmed down or turned off during the rest of the time.

Kunz et al. [10,11,12] employed LC shuttered LCD projectors to generate an active stereo display for their blue-c system.

There have been a small number of other approaches to provide multiple users with individual stereoscopic images. The two-user Responsive Workbench [1] displays four different images in sequence on a CRT projector at 144Hz, which results in 36Hz per eye per user. They also developed custom shutter glasses for cycling between four eyes. Blom et al. [3] extended this approach to support multi-screen environments such as the CAVE[4]. Barco [2] developed the "Virtual Surgery Table", which provides two users with individual stereoscopic images by combining shuttered and polarized stereo into one system.

3. Hardware Setup

Our system consists of a pair of LCD projectors and shutter glasses for each user, mechanical or LC shutters in front of the projectors, and a number of computers. Each computer generates an image pair for a single user and drives a pair of LCD projectors (Fig. 2). Alternatively we could use an individual computer to generate an image for each eye of each user, but this would require frame precise synchronization between pairs of computers. The projectors' shutters and the shutter glasses are synchronized through a micro controller.

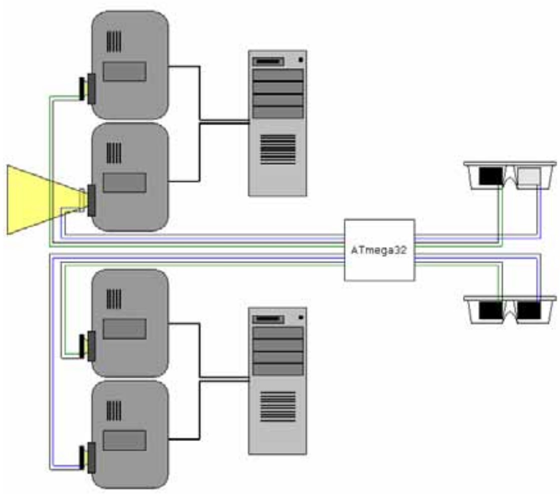

Figure 2: The hardware setup used for two users and four LC-shuttered projectors. There is a shutter in front of each projector. Only one shutter is open at a time. The shutter mechanism is completely decoupled from the image refresh and the computer. The Atmel ATMega32 micro controller drives the shutter glasses and the shutters in front of the projectors.

3.1 Liquid Crystal Shutters

We used standard tethered gaming shutter glasses (Elsa Revelator) for shuttering the users' eyes. For shuttering the projectors we took the same gaming shutter glasses apart and mounted the shutters directly in front of the projectors. The shutters are a little too small to cover the whole image, but for a test setup they were quite sufficient. The original electronics of the shutter glasses were removed and we used a micro controller to generate the required signals.

LC shutters are closed if a positive or negative voltage is applied. Otherwise they are open. For fast and continuous on/off switching of the shutters it is necessary to drive them with alternating polarity to avoid memory effects. Our experiments showed that our particular shutters provide the best results if +-15 Volts are applied. We were able to run the shutters at up to 300Hz with only little cross talk. Currently we feed exactly the same signal to the shutters in front of the projectors and to the shutter glasses. As a consequence the closing signal for a projector and the corresponding eye shutter arrive exactly at the same time as the opening signal for another projector and eye. This approach might contribute slightly to the cross talk, but we have not yet experimented with slight delays nor do we know the exact open and close timing behavior of the shutters.

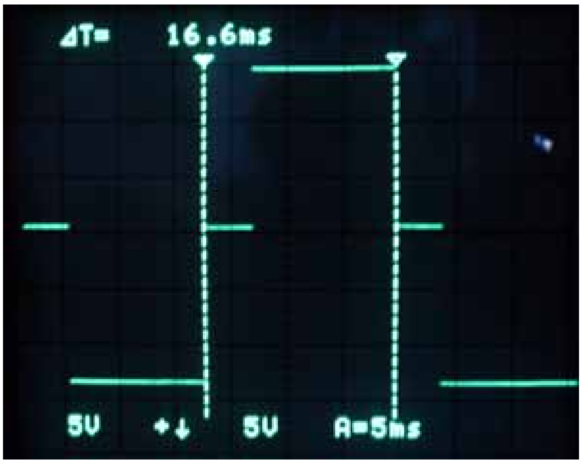

Figure 3: Driving signal for the shutters in two-user mode. The signal is alternating between 15V (closed), 0V (open), and -15V (closed). One open-close cycle is 16.6ms long – 60Hz per eye per user – resulting in a virtual time-sequential video signal of 240Hz.

For our first experiments we used older LCD projectors with around 1000 Lumens. The shutters in front of the lenses did not warm up in this case. For the final tests we used projectors with 1700 Lumens, which resulted in significant heat development in the shutters. We had to install a fan to cool the shutters down. Larger shutters would allow us to move away from the LCD projectors, which would distribute the heat across the larger shutter surface. Smaller fans could be mounted near each shutter to avoid heat problems.

3.2 Mechanical Projector Shuttering

For the mechanical shutter approach we used a spinning plexiglass disc in front of the projectors. For security reasons the spinning disc is encased in a wooden cage (Figure 4). The straight forward layout for the spinning disc would uses three opaque quarters and one transparent quarter. If we open the shutters immediately once the transparent quarter reaches a lens, we introduces crosstalk since one of the other lenses is still open. If we reduce the transparent quarter such that it fits right in between the projector lenses such that only one lens is open at a time, we reduce the cross talk significantly (Figure 5). The overall brightness is appropriately reduced. Alternatively we could stick with the three quarter / one quarter layout and open shutters only during times when only one projector lens is open. This introduces phases during which all shutter glasses are closed.

Other layouts are possible, which divide the disc for example into eight zones (Figure 6). Two zones would be transparent, the others opaque. Each rotation of the disc would open each shutter and projector lens twice. Such a setup would divide the required rotation speed in half, but decreases the actual light output if the disc size is not enlarged. The diameter of the exit pupil of the projectors in relation to the circumference of the disc should be small, since the actual shutter timing depends directly on it.

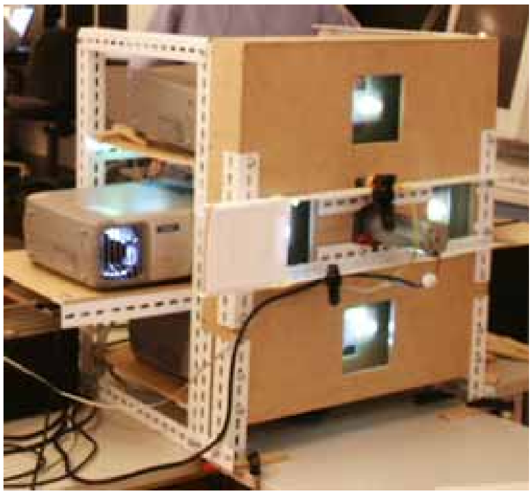

Figure 4: The spinning disc is contained in a wooden cage separated from the projector rack to avoid vibrations of the projectors. The small motor in the middle spins the disc.

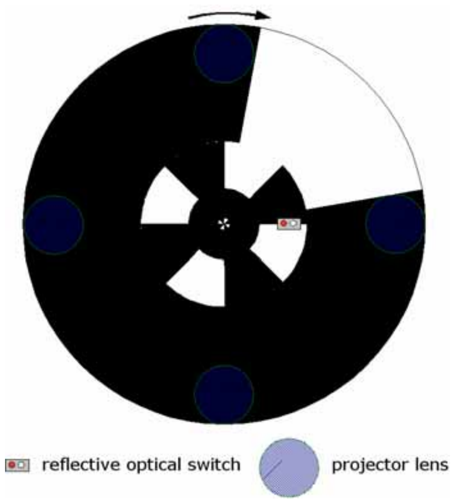

Figure 5: Shutter disc for the two-user setup. Four projectors are located around the axis of the disc. One quarter of the disc is open, three quarters are closed. An reflective optical switch is used for generating the synchronization signals for the shutter glasses.

We currently use a single reflective optical switch to generate the control signals for the shutters. The inner ring of the disc is separated into four black and four white zones, which generate the clock for the shutter glasses. Our current implementation requires that the spinning disc starts always in a defined orientation to shutter the LC shutters in the correct order. We could also install an additional optical switch which detects the opening of the first video projector and provides an initialization for the clock signals of the inner ring.

3.4 Heart of the System: A Micro Controller

We use the ATMEL ATMega32 micro controller to drive the shutter electronics for the projectors and glasses. The micro controller is mounted on a small board together with some drive electronic for amplifying the output signals. The micro controller board is plugged into an evaluation board that provides power to the micro controller and allows easy access to all the inputs and outputs of the micro controller (Figure 7). The micro controller board supports:

- 16 digital configurable input/outputs
- 8 analog inputs
- 8 PWM outputs

We use only the amplified digital outputs to drive the shutter glasses and the digital inputs for reading the signals from the reflective optical switches. With a maximum of 16 outputs we could drive 4 users and 8 projectors at a time.

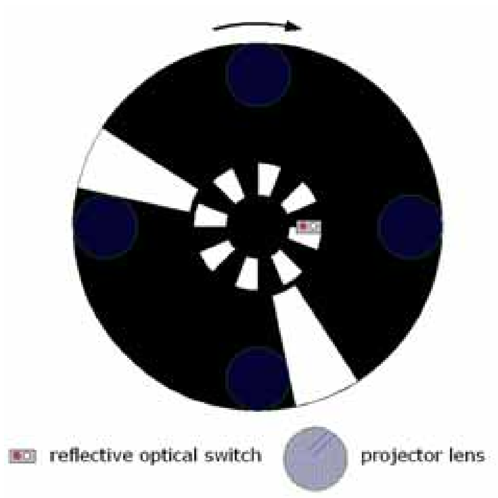

Figure 6: Alternative layout of the spinning disc for two users. During one rotation each projector is opened twice.

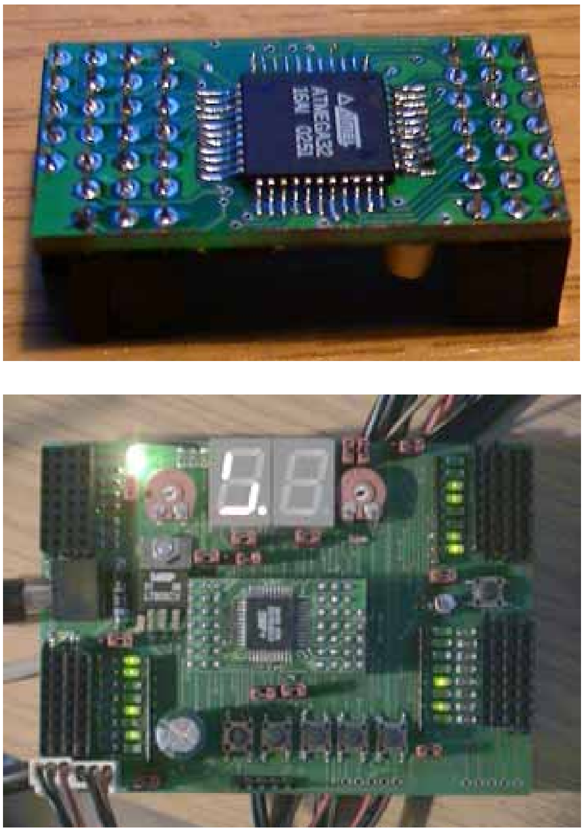

Figure 7: On the top: the Atmel micro controller board. On the bottom: the evaluation board.

4. Experiences and Discussion

The setup for the LC shuttered projectors is completely implemented and tested for two users at different frequencies. The mechanical shuttering setup with the spinning wheel has been built and tested at up to 200Hz refresh rates. For our approach we used LCD projectors. LCD projectors modulate light on a per pixel basis for the red, green, and blue channel. The light output per pixel during a frame is basically constant and the shuttering approach shows this image for a certain time slice. Single chip DLP projectors employ a color wheel and display the red, green, and blue channels for a single frame in sequence. In addition, the required brightness of a pixel is accumulated over time by the micro mirrors on the DLP chip. The shuttering approach would slice a certain fraction of a frame, which would result in incorrect colors for a single frame and an interference between the DLP refresh rate and the shutter frequency over time.

4.1 Mechanical shuttering

The spinning disc approach leads to really fast rotations if it is used in its simplest form. For example if we want to achieve 200Hz, 50Hz per eye per user, we need to spin the disc at 50 Hz or 3000 rpm. We tried this approach and we were able to spin the disc at up to nearly 3000 rpm with a small DC motor. At the maximum rotation rate and 49.5 Hz per eye per user the image was basically flicker free. At 45Hz we saw minimal flicker. At lower refresh rates the flicker increased and below 40Hz the flicker was very noticeable.

Our current disc has a diameter of around 40 Centimeters (14inches) and is made out of 3mm plexiglass. The minimal size of the disc is mainly determined by the size of the projectors and the distances of the projector lenses, but the disc size affects directly the time it takes to close and open a projector lens. Larger discs reduce this time significantly, but it is difficult to fully avoid vibrations and noise of large spinning discs. We did not measure the noise of our system, but it was significant and annoying after a while. The cage around the spinning disc could be used to dampen the noise.

One of the main advantages of the mechanical shuttering approach is the possibility to completely avoid crosstalk between projectors. There is always some cross talk due to the shutter glasses unless they would be replaced by mechanical shutters as well. In addition LC shutters are not fully transparent while they are open. A transmittance of only 32% during the open state is reported for Stereographics Crystal Eyes shutter glasses (www.stereographics.com). Thus it is very worthwhile to look at mechanical shuttering systems, which provide 100% transmittance during their open period even so the LC shuttering approach is much easier to implement.

4.2 LC shuttering

Our first tests investigated the cross talk at different frequencies and supply voltages for the LC shutters. The least cross talk was found at about 15 Volts. Over 15 Volts the shutters started to show some speckles, which indicates their voltage limitations. Nevertheless we were running the shutters at 15 Volts for many hours without any degradation in image quality, but it is possible that this is above the specs. There was slight crosstalk, which was barely perceivable while viewing stereoscopic images.

Our shutters are quite small and they barely cover the exit pupil of the projector lens. If we use the full resolution of the projectors, we are seeing refraction artefacts from the boundaries of the shutters, which results in some rainbow effects across the images. If we limit ourselves to about 80 percent of the shutter surface, these artifacts are no longer visible.

We experimented with different shutter switching frequencies in the range of 140Hz to 400Hz. We implemented the timing control for two, three, and for users. For two users, each shutter (eye) was open for one forth of the time, for three users for one sixth, and for four users for one eighth. The tests were performed with two pairs of glasses and four projectors, but the timing was already correct for two, three and four users. The results of these tests:

Two users:

- 140Hz: flickering
- 160Hz: very little flicker
- 200Hz: no flicker
- 240 Hz: no flicker, good image
- 280Hz: no flicker, very good image

Three users:

- 240Hz: slight flicker
- 270Hz: barely flickering
- 300Hz: no flicker
- 360Hz: dark image, pumping

Four users:

- 240Hz: flickering
- 280Hz: slight flicker
- 320Hz: very slight flicker

- 360Hz: dark image
- 400Hz: very dark image

Above 320Hz our shutters did not open fully anymore and the images got quite dark. At around 400 Hz the shutters started to show some stripe patterns and did not work properly anymore. At some frequencies he image got slightly darker and brighter with a low frequency. We found that this problem was related to an interference of the power frequency of our room lights and the shutter frequency.

It was amazing to see that these cheap LC shutters worked quite well even at such high frequencies. For the two user scenario, our favorite frequency was 280Hz, which resulted in a stable and completely flickerless image. But even at 160 Hz the flicker was not really very disturbing, but we did not use the system for long working periods. We did not perceive any difference in brightness between 160Hz and 280Hz for two users, even though the state transition time of the shutter glasses should start to play a role. In particular the transition from the closed to open state is longer than the inverse transition. For three users, the image was slightly darker than for two users, since each eye was exposed to an image for only one sixth of the time. There was little flicker above 270Hz. For four users, the image was clearly darker and there was still slight flicker at 320Hz. At higher shutter frequencies the image got much darker and it was hard to judge the image quality.

We have also investigated two different sequences of presenting the images to the left and right eye of each user – similar to the approach in [1]. The viewer interleaved sequences displays the left eye images of all users in sequence and then the right eye images. The viewer sequential method displays the left and right eye images for each user directly in sequence. Surprisingly, we did not notice any perceivable differences, even when switching directly back and forth.

4.3 Driving the Multi-User setup

We implemented some basic test scenarios based on the distributed virtual environment framework Avango [16]. Avango's distribution mechanism was originally developed for distributed applications. In our case we use this feature of the system to drive a small PC-cluster in a master-client fashion. One cluster node runs the master application and computes the left and right eye images for a single user. The client nodes have synchronized copies of the master's scene graph and compute the images for the view points of their assigned users.

Figure 4: An image taken directly from the projection screen. It shows four images overlayed on top of each other. Two images are displayed for the left user's eyes and the other two images for the right user's eyes.

One of the big advantages of the shuttered multi-viewer approach is that images can be generated on different computers without requiring perfectly synchronized graphics as long as the left and right eye of a user are synchronized. Slight frame delays between the two users are in general not recognized.

5. Conclusions and Future Work

We have reported on the implementation of a multi-user active stereo system based on shuttered LCD projectors. We have successfully implemented shuttering of four projectors to support two individual users with perspective correct stereo views. Our users did not perceive flicker above a refresh rate of 200Hz. We experimented with LC and mechanical shutters for shuttering of the projectors. For the LC shutter based approach we have also experimented with shutter timings for three and four users, which indicate that shuttering should also work for these cases. The main limitation of our approach is that the each projector is exposed to a user's eye for only a certain fraction of the time, which reduces the overall brightness accordingly.

For the mechanical shuttering approach we are planning to do further experiments using a disc with more than one transparent zone to reduce the required rotation speed. We will also investigate other means for mechanical shuttering, such as a separate disc for each projector or projector pair. There is also the question if the mechanical approach scales beyond two users.

We plan to set up a system for four users, which requires brighter projectors and other liquid crystal shutter technology such as Ferroelectric Liquid Crystal (FLC) shutters.

Similar to the approach in [2], we are going to combine passive stereo and active stereo. The shutters in front of the projectors are already polarizing the light according to their orientation. We just need to turn the shutters by 90 degrees on a pair of projectors and in the corresponding shutter glasses. The combination of these approaches will allow us to support 4 to 8 people with individual stereo pairs.

6. Acknowledgements

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