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Microlithography for Halftoned Gobos

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Abstract

Beacon AB has been producing Gobos for some time. A Gobo is a small round sheet used in projectors almost like a slide. It is used mostly in the commercial and entertainment business. Today these Gobos are created by using a film (also called mask). A digital exposure machine called LIOS has been developed to make it possible to create Gobos using direct exposure. This means a film will no longer be necessary and it will also make the process faster and cheaper.

To be able to use LIOS in the industry a lot of work still has to be done. An image is sent to the display in LIOS. This image comes from a computer connected to LIOS and at the end of the process it will be reproduced on the Gobo. This image can be modified before it is sent to LIOS so that a better result can be achieved in the end. The problem is that once the process is complete the image will be binary, which means halftoning is going to be used. The goal of the research described in this paper is first to test the properties of LIOS, second to create a halftoning method especially designed for those properties.

The result of this thesis is an AM (Amplitude Modulated) method that uses a modified threshold matrix. Using this method would not give a satisfying result unless some of the distortions could be corrected somehow. This can however be done using a property available for the display in LIOS. The display can handle grayscales but since etching is used later in the process the final result will be a binary image (only black and white). This means that even though the image will be binary in the end, these grayscales can still be used to improve the result. The equipment that was available when this thesis was done was not fully developed why the grayscales are used to correct distortions.

The resulting method will most likely be good enough to produce Gobos with a satisfying quality. The method has never been used before and it introduces a new way of making corrections for halftoning. There are still some practical problems left to solve before LIOS can be used to reliably produce Gobos. Using better equipment can solve several of these problems but not all of them.

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1 Abbreviations

AM:
Amplitude Modulation.

Anisotropic:
Property of a material that produces different strains when identical stresses are applied in different directions.

Condenser lens:
A mirror, lens, or combination of lenses used to gather light and direct it upon an object or through a projection lens.

Ferroelectrics Liquid Crystal on Silicon:
Technology in which the surface of silicon chips, made by standard processes, is coated by ferroelectrics liquid crystal. (FLCOS)

FLCOS:
See Ferroelectrics Liquid Crystal on Silicon.

FM:
Frequency Modulation.

Gobo:
A small glass slide which has a layer of aluminium or colors and a layer of photoresist on top of that. The photoresist is exposed and the aluminium layer is then etched. This etching is usually an image. The Gobo is used in projectors to display the image on the Gobo in enlargement.

IMCDP:
A modern halftoning method.

LIOS:
The digital exposure machine that the research in this thesis relies on.

Lithography:
A printing process in which the image to be printed is rendered on a even surface, as on sheet zinc or aluminum, and treated to retain ink while the no image areas are treated to repel ink.

Photoresist:
A light-sensitive resist which is exposed and developed prior to a printing or etching process. The exposed areas of the surface serve as a mask.

2 Introduction

This paper will describe the development of a new method to create Gobos. The work will, in the end, hopefully lead to a product that can be used by the company Beacon AB. There is currently a method used today to produce Gobos that uses a mask. Instead of a mask a digital exposure machine called LIOS (Lithography optics design) will be used. By connecting LIOS to the graphic card in an ordinary PC, it is possible to reproduce the image displayed on the monitor connected to the computer to the top layer of a Gobo. After this has been done the remaining process is the same as the one used today as described in section 2.2.1 “Creation of Gobos today”.

However, using a digital exposure machine instead of a mask has several expected advantages. The main reason to use LIOS is that it will be possible to produce Gobos without any film. This will make the process faster and cheaper. When using a mask the smallest possible halftone dots are around 10x10 µm. The pixel size in LIOS is around 5x5 µm. Using LIOS it is also possible to handle grayscales before etching. This theoretically means, that it could be possible to use dots that are even smaller than 5x5 µm.

2.1 Beacon AB

Beacon AB makes a living on producing Gobos. These are used in projectors to create an image on a projection plane. To get a better picture of how Gobos works you could say that they are used almost like slides. The grayscales in the image are created by halftoning, instead of absorbing light like photographic film does. Gobos are usually used in the entertainment business like theatre and TV or advertising.

The theory of how projectors works are showed in the figure below:

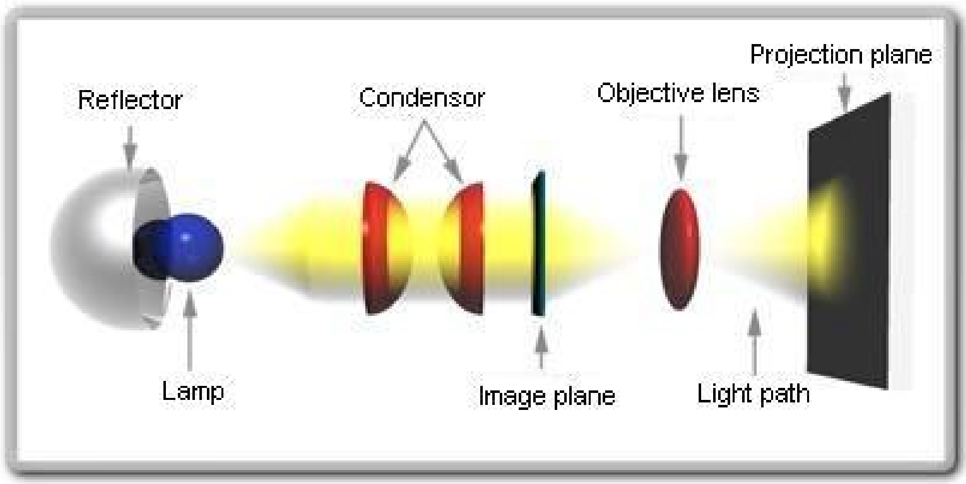

Figure 1: The theory of a projector. [2]

A lamp emits light, which passes through a condenser lens to make the light parallel. The light then passes through the image created on the Gobos and is focused through an objective lens. The image is then projected on the projection plane, which can be any surface even enough not to affect the displayed image. The projection is a reversed, mirrored image.

Today Beacon AB produces Gobos in either grayscale or color. The customer chooses these from a standard collection of images or an especially ordered image. A few examples of Gobos created by Beacon AB are shown below.

Figure 2: Examples of Gobos taken from "Gobokatalog 2004, Beacon AB"

2.2 Gobos

The production of Gobos today is based on a lithographic process. The steps included in this process will be described shortly (figure 3).

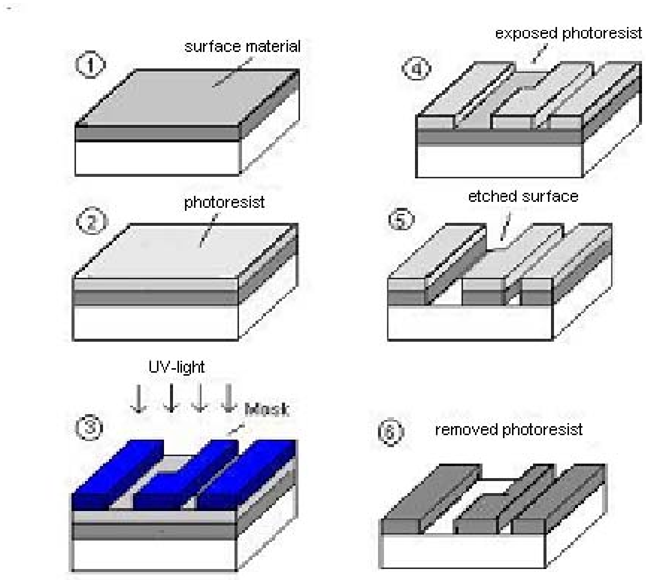

Figure 3: The principle of how the production of Gobos works today. [6]

2.2.1 Creation of Gobos today

The first part of a Gobo is a glass slide, which is then treated in a vacuum chamber to create the first layer, which is either aluminium or a layer of color (1). This layer is what in the end creates the image on the Gobo. The layer on the top of the Gobo consists of positive photoresist (2). On top of the photoresist a mask is applied and light is then sent through it (3).

This exposes the photoresist, which is then developed. This means that the part of the photoresist that has been exposed is removed, usually by using a chemical (4). Using etching the layer(s) that consists of either aluminium or color is then removed (5). In this step the photoresist will protect the parts of the layer that is not supposed to be etched. There are two methods to do this. One method uses plasma and the other uses a chemical to remove the layer. The rest of the photoresist is then removed before the Gobo can be used (6).

To create a Gobo in color three layers of glass are used with the colors yellow, magenta and cyan. The layer of aluminium is still used here and the pattern on the Gobo is created by etching these layers one at a time and putting them all on top of each other to create the color display.

2.2.2 Problems with the current method

There are several problems with the method used today compared to the one being evolved. First an original film needs to be created so that you can use it to create copies, which has limitations to the resolution. The original film is also easily worn out and needs to be replaced now and then, which means new originals must be created. This requires both time and material, which makes it rather expensive. There are also many steps in the process. More steps means there are greater risks of mistakes and it also means the process will take more time, thus making it more expensive. The number of steps should be as few as possible to create a better result and cheaper production.

2.2.3 Using LIOS, the new method

The method that this thesis will cover is currently being developed. Instead of using a mask the new method will now use a digital exposure machine called LIOS (Lithography Optics Design). A computer is connected through a graphics card to LIOS. This makes it possible to reproduce the image shown on the screen of the computer into the display in LIOS. Then a light source is placed so that the light is transmitted into LIOS. The light then exposes the photoresist so that the image on the screen from the computer is reproduced into the top layer of the Gobo. After this step the Gobo will be treated with the conventional method using etching etc.

To gain a better understanding of the differences between the new and old method, a comparison can be seen in figure 4.

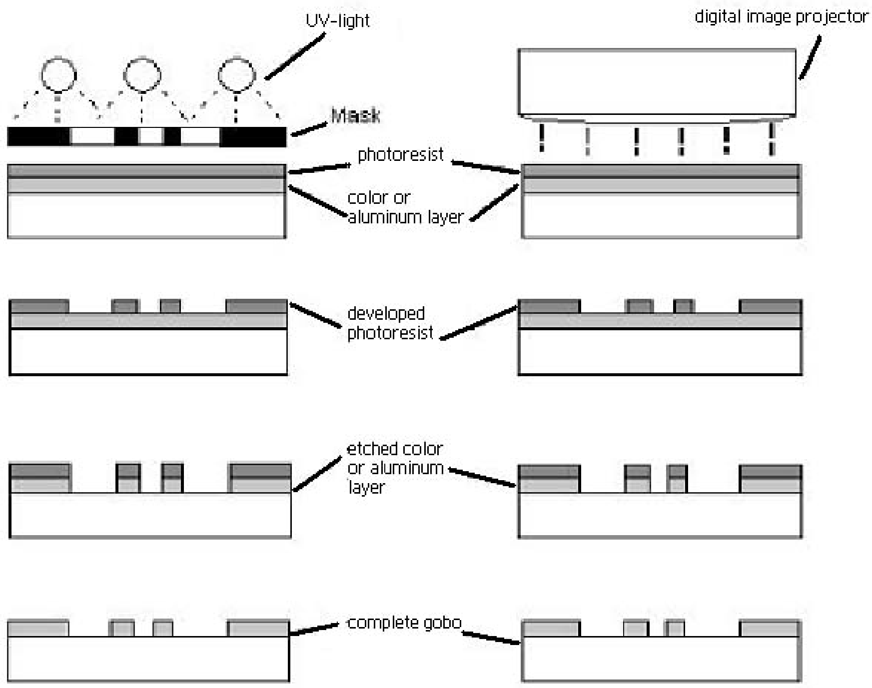

Figure 4: Comparison of the methods used to create Gobos [6].

The direct exposure is supposed to work according to the following theory when everything is done (figure 5):

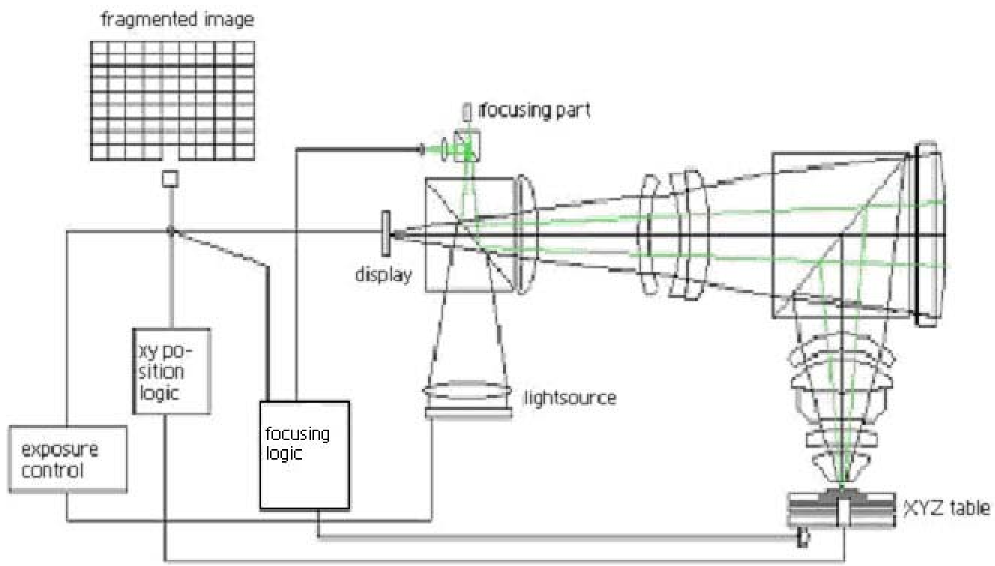

Figure 5: Sketch over the basics of LIOS and how the light travels before it hits the Gobo [6].

1. The top layer of the Gobo (the photoresist) is scanned in the X- and Y-direction.
2. The image that is going to be exposed is analyzed in a computer and halftoned so that each halftone dot is built up by a certain amount of pixels.
3. The image is divided into fragments with 1280x1024 pixels since that is the resolution of the display. Each pixel will be about 5 µm.

4. Black fragments are skipped since black pixels do not affect the exposure on the Gobo in any way.
5. The fragments are placed on a stack.
6. The fragments are sent in one after one into the display at the same time as information about the position is sent to the XY-positioning logic.
7. The XY-table is placed into the right position and the light source is turned on which leads to the photoresist being exposed.
8. When all fragments have been exposed the table is pushed forward in position.

The image needs to be focused within a few micrometers and it needs to be quick. This is preferably done automatically. Theoretical calculations have been done to make automatic focusing but it did not work practically. The reason is that it wasn't possible to distinguish between the real signal and the reflected light as decribed in section 5.1.1 "Auto focusing". Therefore focus will be a big problem in the continuing work with the development of the new method. The work done so far has not tested images covering the whole Gobo why the exposures done today only cover one fragment of 1024x1280 pixels.

2.3 Purpose and disposition

The purpose of this project is to get as far as possible developing a halftoning method designed for LIOS. The goal is to create a halftoning method that can be used in industry, when all other problems are fixed. The goal is to make it possible to modify the image before it is exposed, to correct for the possible errors that occur while exposing.

2.4 Planning

The plan used in this thesis has been to first test the different properties of exposures. After the initial testing is done most of the properties should be known. This should make it possible to analyze the result and make a guess of what kind of halftoning that could work.

2.4.1 Limitations and possibilities

The initial part will be to identify the limitations and possibilities and when that is known the second part of the project can start which will focus on creating a halftone method defined specifically for this purpose. An important part of identifying the properties of the exposure will be to draw a dot gain curve. Knowing it makes it a lot easier to adjust the brightness of the image. The dot gain curve will be explained further in this paper in section 3.2 ”Dot gain”.

Before this thesis was done there were very little knowledge about how good results that could actually be achieved using LIOS. However, some problems were already known.

The problems identified from the start were the following.
1. Focus, the auto focusing system does not work. This means that some help to focus will most likely be necessary. The best way would be if it could be done automatically but if this is not possible, it is important to make it as easy as possible to focus LIOS manually.
2. There are variables that can differ between different experiments like time of exposure, etching and developing. Testing needs to be done to know these time slots.
3. Other practical problems that might cause trouble, for example damaged components or inadequate software or hardware. The economy for this project is limited, which means this could most likely be a problem.

3 Background theory

This chapter will cover some background theory that is needed to understand the rest of this paper.

3.1 Halftoning

In many situations an image with different colors is wanted but the tools used to produce the image can only handle binary images. In this case halftoning is used and the result is still a binary image but from a certain distance the human eye will perceive it as different colors or grayscales. An example of when this is useful is printing. When printing a newspaper only two colors are available (usually black and white). It is not possible to print grayscales. However, newspapers contain both text and pictures. As long as there is only text then black and white is enough but to be able to print an image grayscales are usually needed. Here halftoning can be used to create those grayscales using only black and white. Halftoning creates an illusion that an image that is binary actually has a continuous scale.

The human eye is not perfect and at a long enough distance it cannot perceive small details. This is what is used in halftoning. The image is divided into small parts. These parts are meant to be so small that the human eye cannot see the details in them. The area in each part is then filtered and the filter used depends on what method is used. This filter makes the image binary and parts that is close to black has a larger amount of the pixels in the area covered while brighter areas has a smaller amount. If the details are so small, that the human eye cannot see them these parts will look like they are different colors instead of just small squares.

Halftoning can also be done in color images as well as grayscale images but since grayscales is what will be used in this project, grayscale halftoning is the only one that will be described here. The methods used for halftoning in color are almost the same as in grayscale images but the halftoning is done in more than one layer (usually 3-4 layers), which makes things a little more difficult to handle, but the principle is the same.

3.1.1 AM halftoning in grayscale images

AM (Amplitude Modulated) halftoning is sometimes referred to as conventional halftoning. AM-filters use a dot that that grows depending on the brightness of the grayscale. The dot becomes more filled as the grayscale becomes darker. The distance between the centers of two dots is always constant. The distance can still vary between different pictures however. The last variable that also can vary is the screen angle. If the dots are placed on a straight line, i.e. with an angle of 90° the human eye can see a pattern in the image. This is something we want to avoid because humans watching the halftoned image should preferably see a continual image without any visual distortions or patterns. Research has proven that the human eye is more sensitive to horizontal or vertical patterns compared to diagonal patterns [8]. Therefore the best angle is usually 45° even though there might be some special cases where another angle might be better or easier to use.

A problem that occurs in AM-halftoning is Moiré-patterns. These patterns occur if the image has repeating structures but these can be made less visible if the screen angle is 45° as mentioned above.

3.1.2 FM halftoning in grayscale images

FM-halftoning (Frequency Modulated) or stochastic halftoning as it sometimes is called is an alternative to AM-halftoning. In FM-halftoning the size and shape of the dots are constant throughout the image but the distance between the dots varies. The name stochastic halftoning comes from the fact that the dots are sometimes placed randomly.

Compared to AM halftoning this method usually gives a better result in details if it is possible to use 1x1 pixel dots. However FM halftoning is an unstable method especially when it comes to dot gain. Dot gain is an effect that make dots bigger as described in section 3.2 “Dot gain”. If all attributes are known it is possible to modify the halftoning to compensate for that. AM halftoning also gives a better result in large homogenous areas.

3.1.3 Hybrid halftoning

To get a better result when a halftoning is a choice is to use a hybrid method. By using a hybrid AM/FM-halftoning method it is possible to use AM halftoning in some areas of the image and using FM halftoning in other parts. The advantage of this is that AM halftoning can be used in the large homogenous areas where it gives a better result while FM halftoning can be used in the parts that has small details. By doing this the halftoning will be a little more difficult to do, which means it will require more work and take longer time to do, but it will (hopefully) produce a better halftoned image.

3.1.4 Line halftoning in grayscale images

Line halftoning is a one-dimensional method that is very stable. This was the method used when computers were first developed. The main advantage of this method is that since it is only one dimensional it is very robust and easy to handle. The big problem also lies in that it is one-dimensional because that means it is not possible to use as many gray-levels as with other methods. Since the halftone points are lines it is easier for humans to actually see that the image is halftoned which is an unwanted effect of this method.

3.1.5 Error diffusion

Halftoning an image will in most cases cause an error, which means the halftoned image does not have the same mean brightness as the original image. A way to make this error a little less noticeable is to spread it out over the image. This will usually make the halftoning dots less visible for humans.

The mathematical work however is greater using error diffusion. The reason is that for every halftoning the error is spread out over the surrounding pixels. This means that instead of making only one calculation for every pixel, several need to be done. The error is usually spread out to the nearest four or eleven pixels. The result of this is that the calculations needed are four or eleven times as many. With modern computers today this usually is not a big problem, and some other image improving method that requires a lot of calculations is also used. This makes error diffusion a rather attractive method to use to improve the quality of halftoned images in most cases and it is rather easy to use.

3.1.6 Threshold halftoning and table halftoning

Halftoning can be done by using either threshold halftoning or table halftoning. Both methods divide the image in small parts. Threshold halftoning uses a given threshold matrix and then compares every small area in the image to that. If a certain pixel is above the threshold then that pixel is set to black and if it is below the threshold the pixel is set to white.

In table halftoning every small area of the image is checked for the average brightness. And depending on the average the area is then covered with a number of black pixels that brings it closest to the average.

Comparing these two, the threshold halftoning is usually better at preserving small details, while table halftoning usually gives a better result in large homogenous areas.

3.1.7 Iterative Method Controlling Dot Placement (IMCDP)

IMCPD is a halftoning method developed to produce high quality halftoning images. The basic idea in this method is that the mean in the halftoned image should be the same as the original. This is done by checking the mean of the original and compares it to the halftoned image. If the halftoned image has a mean that is lower a dot is placed where the original image has the highest density. This is then continued until the halftoned image has at least the same mean as the original. ([3] page 4-5)

This method is one of the best that exists today. The problem compared to normal AM or FM halftoning is that there are rather many calculations done so it requires computer power and time to do it. There are other methods that gives a similar result but they are usually a bit slower.

3.2 Dot gain

When printing an image the dots usually become a bit bigger because of the printing process. This will make the image look a lot darker and a lot worse than the original image. Therefore a dot gain curve is usually produced that specifies what percentage of coverage that should be sent to gain the result that is closest to the original image. An example of when this is done is when calibrating halftone images for a specified printer. The same idea can be used in this thesis. If it is possible to calculate a dot gain curve for the exposure in LIOS it would mean it would be possible to modify the image before it is sent to the display in LIOS and take the dot gain into account. This means in theory that some errors that occurs while the image is sent through the system can be repaired by modifying the input image. If this property of the system is known it can be used to greatly increase the quality of the resulting picture if the dot gain is large. If the dot gain is small the correction would not make any sense.

3.2.1 Point Spread Function (PSF)

All optical systems, including the human eye has a blurring effect. This blurring effect varies a lot between different optical systems. An example of this blurring effect is if a person that is shortsighted looks at something far away. Then that person receives an image of the object blurred. All optical systems have this effect more or less and it can be simulated using a point-spread function (PSF).

The PSF can be obtained using equation (1) where x(n, m) is the blurry image obtained from the original image s(n, m) and h(n, m) is the discrete Point Spread Function for the imaging system.

$$x(n,m) = \sum_{a=-\infty}^{\infty} \sum_{b=-\infty}^{\infty} s(n+a, m+b)h(-a,-b) \qquad \text{eq. (1)}$$

If the properties for h(n, m) are known these could be used to create a simulation of the exposure. More information about this is available in section 5.5 ”Simulations of the exposure”.

4 The resources available

This chapter will describe the available resources that were used when doing the experiments in the thesis.

4.1 The digital exposure machine LIOS

To get a better understanding of the problems occurred and solutions used it is important to have a basic understanding of how the optical system used in this project works. The optical system used to create Gobos with the new method is called LIOS (Lithography optics design) and it is a digital exposure machine. LIOS has been created by VTT Electronics in Finland in cooperation with Beacon AB (figure 6).

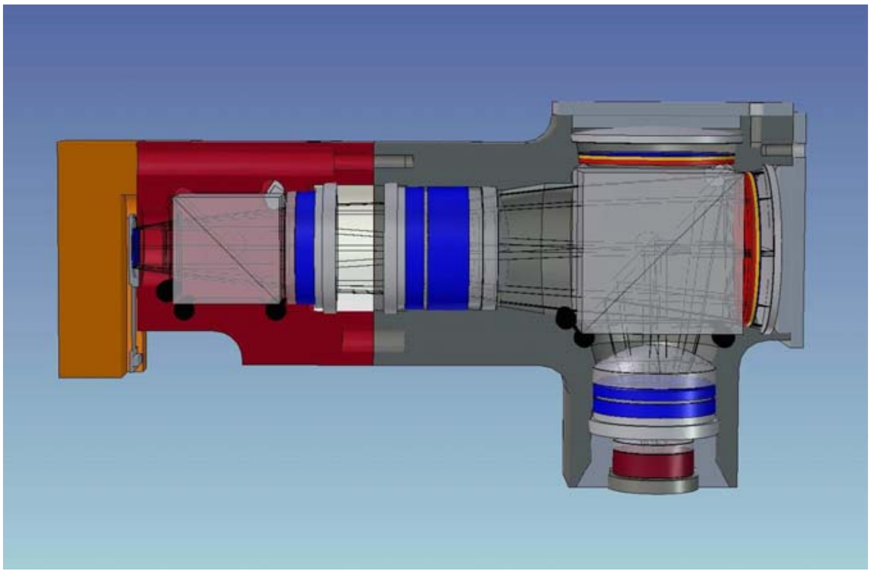

Figure 6: Cross-section of the lens [6].

Below is a more technical figure of how LIOS looks like (figure 7).

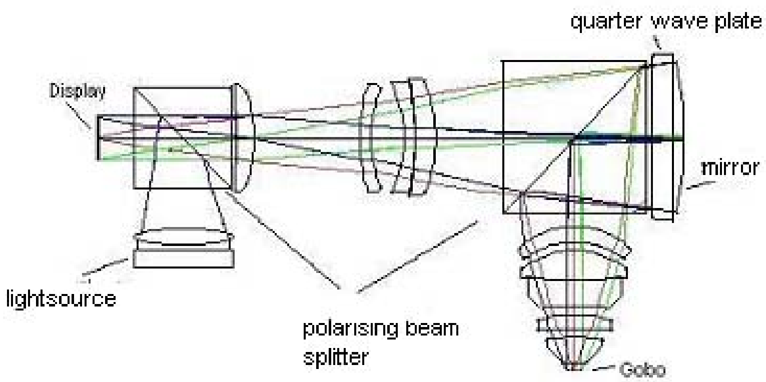

Figure 7: Technical details of LIOS. [6]

The image is sent from the computer to the display. The blue light with wavelength 405 nm is sent from the lightsource, polarized and reflected 90° which means it hits the display of model

FLCOS (Ferroelectrics Liquid Crystal on Silicon). The display reflects the light and turns the polarization for the pixels that is going to be exposed so that those pixels passes the prism on the way back and the rest is stopped. The filtered light then passes the lenses and is reflected in the mirror. The quarter wave plate changes the direction of the polarization so that the light is reflected 90° by the second prism down to the Gobo. The filtering done by the first polarizing beam splitter makes the correct part of the photoresist on the Gobo to be exposed.

4.1.1 Polarizing beam-splitter

LIOS uses two different beam-splitters in the prisms. The light that passes through a polarizing beam-splitter will be either transmitted or reflected depending on the polarization of the light. If the polarization of the light is vertical then all light will be reflected (figure 8 case A). In the case of the light being horizontally polarized all rays will pass through without being affected (figure 8 case B). If the angle of the polarization is 45° then half the light will be transmitted and the other half will be reflected (figure 8 case C).

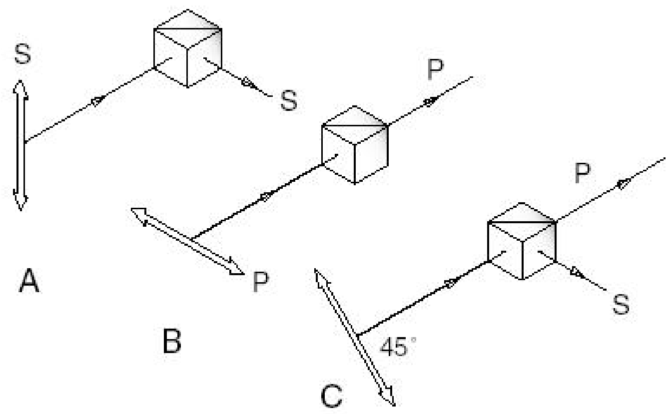

Figure 8: Transmission and reflection of a polarizing beam-splitter ([5] page 19).

4.1.2 The light source

LIOS is built for blue light and therefore the light source used sends out blue light with a wavelength of 405 nm. The light source used at the start of the project did not have a uniform light and was significantly stronger in the middle of the image. This had the effect that either the middle or the edges of the images could be made with good quality. The light source had 16 diodes of the type GaN. The diodes came from Ledtronics, model: ”L200CUV405-8D” [4]. After a while the light source had also been damaged so that only one third of the original effect of the light was still working.

Because of the first light source being damaged and the results not being good enough, a new light source was developed and tested. It was significantly weaker than the first one because the time used to expose the image was increase from a few minutes to over ten minutes. The light was a bit more evenly distributed compared to the first light source though. This light source also had diodes from Ledtronics but this one had 90 diodes of the type: ”L200CUV405-12D” [4]. This light source made it possible to create images of a bit better quality.

A third light source was also developed and tested. It was a little weaker than the second but the light was supposedly more evenly distributed on the image. It was created from an effect diode from Roithner-lasertechnick model: ”LED405-66-60” [7].

4.1.3 The display

The image that is going to be exposed is sent to the display from a computer. The technology used in the display is called FLCOS (Ferroelectrics Liquid Crystal on Silicon). The projector has 1280x1024 pixels with a distance of 12 µm from one pixel to another. The magnification of the lenses in LIOS is 0.3748, which means the pixels projected on the Gobo will be around 5 µm. CRL Opto produces the display and it is currently optimized for green light instead of blue light, which is what will be used. The reason why green light can't be used is that photoresist sensitive of green light does not exist.

4.1.4 The quarter wave plate

A quarter wave plate is produced from an anisotropic material. This means there are two optical directions in which the light can pass it, one ordinary and one extraordinary. If linear polarized light travels through it and the polarization direction is 45° then half the light will travel in the ordinary direction while the other half will travel in the extraordinary direction. The light that travels through the quarter wave plate will also be circular polarized if it was linear before, and linear polarized if it was circular before.

The meaning of the system is that the quarter wave plate turns the polarization of the light 45° every time the light passes through it. The LIOS is built so that the polarized light first passes the polarizing beam splitter and then the light passes through the quarter wave plate, which makes the light circular. The light is then reflected in a mirror back through the quarter wave plate, which means the light is now again linear but the polarization has been turned 90°. Now when the light travels back into the polarizing beam splitter the second time the light is reflected downward 90° so that it hits the Gobo.

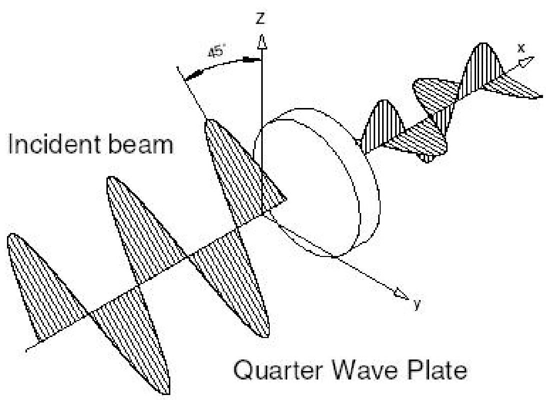

Figure 9: Polarization of light passing through a quarter wave plate ([5] page 20).

4.2 The computer

A PC has been used to be able to send the image to the projector. The computer was also a useful tool for analyzing images with the software MATLAB. To make the experiments repeatable a short description of the most important software and hardware on the computer will be listed here.

4.2.1 Hardware

The hardware on the computer was the following:

- A video unit to be able to connect a camera other than a web cam to the computer.
- A mother board from MSI
- An Athlon XP 2500 processor
- 256 MB RAM
- An ATI Radeon 9200 graphic card

4.2.2 Important software

The most important software used on the computer was the following:
- Windows 2000 as operation system
- MATLAB v 6.5 to analyze, modify and create images
- Image viewer version 2.0 to view the images

4.3 Special chrome Gobos

Mostly Gobos with a layer of aluminium has been used as described in section 2.2 ”Gobos”. But to get a better etching profile Gobos having a chrome layer instead of an aluminium layer has been produced. These Gobos has the advantage of being less sensitive in the etching process. However, the drawback is that they are more expensive to produce. Because of that they have only been used a few times.

4.4 Microscopes

In this thesis two microscopes have been used. One to be able to study the result after the Gobo has been etched and one to examine the image reflected back from the Gobo when focusing. The microscope that has been used to look at the result has a 16x enlarging ocular and 4x, 10x, 40x and 100x zoom. The microscope used to focus was originally bought to look at printed circuit boards. It has a continuous built in zoom with an unknown range and the ocular has an enlargement of 10x. A microscope with higher enlargement or zoom would have been useful, but the big problem here was to be able to look at the reflected image the microscope have to be very big and cumbersome. This meant that the small microscope used to look at the result would not have been big enough and this was also the case with many other microscopes.

4.5 Digimatic micrometer

Since the automatic focusing did not work, each Gobo must be focused manually. A difference of a few µm can make the difference between a good and a bad focus. Therefore an instrument was needed to measure the thickness of the Gobos. The tool used was a digital micrometer from Mitutoyo. The accuracy of the micrometer is ±2 µm. Since focusing must be very precise, the error is probably a bit too big to get a perfect result.

4.6 Cameras

In the beginning of the project, cameras were not meant to be used, except to document the result. For the documentation a color camera has been used to record through the smaller microscope to catch documentation images. A few weeks from the start of the project there come up an idea to use a camera for focusing. A normal web cam was tried at a first stage, but that was not good enough so a camera only able to perceive grayscales, which had earlier been used in security was used. This camera had better contrast. The properties of the cameras are unknown but they were rather cheap, which means that their quality probably was poor.

5 Testing the properties of the exposure

This chapter will describe how the development of the new method started. It will give a short description about the methods used and the problems it had.

5.1 Focusing

An important part to get a good exposure is to be able to focus very precisely. Changing the distance between the Gobo and the last lens does this. If the focus is too bad then the image will be very blurry and small details in the image will disappear when the exposure is done. Therefore being able to focus is a very important part of the project that must be done.

5.1.1 Auto focusing

Another thesis has been done by Ida Nordvall to try to create an auto focusing system [6]. This had been done using a similar technique that is used when determining the focus in a CD-ROM. A green laser with wavelength 532 nm was used in this project. LIOS was however built for blue light. This caused a problem when not reflected light of the laser went through the system with full intensity. But to be able to use the auto focusing system, the reflected light coming from the Gobo needed to be seen. The reflected light had an intensity of less than 1/1000 the intensity of the direct light. What this means is that the reflected light was drowned in the direct light and could not be detected, so the auto focusing system could not be used in this project. It will hopefully be possible to use it later after some modifications has been done. Without some kind of auto focusing it will be very difficult to use LIOS to produce Gobos at all.

5.1.2 Manual focusing

Since the auto focusing system did not work a manual focusing method had to be used. Therefore a microscope was used to look directly at the reflected image coming from the Gobo. A normal unused Gobo does not reflect enough light. To be able to see the reflection a thin layer of a florescent color was applied on the Gobo. The reason to use a florescent color is that it changes the wavelength, which makes it easier to perceive structures. A longer wavelength also passes the prism in LIOS more easily. From the start the layer was just drawn with a pencil. This method was not very good because the pencil made marks on the Gobo, which caused the thickness of the layer to differ a little. A few weeks later from the project start however a little more work was put into making a more even layer and another color was also used which made it a lot easier to focus. Manual focusing is not perfect but it is good enough in this project.

5.1.2.1 Problems with manual focusing

Even if manual focusing was used it does not mean it didn’t have any problems. Manual focusing always has an error in the human factor. A human does not have the ability to make the focus perfect. Neither can a human correctly repeat the experiment with the exact same distance to the Gobo. For every Gobo the thickness is a little different and the focus needs to be adjusted accordingly for every exposure. Because of this, it is not realistic to assume that a human can keep the exact same focus in all the tests. This causes problems because it means that there is another unknown variable that must be taken into account when doing experiments. So if something new is tested and a better/worse result is achieved it does not necessary mean that the thing that was tested was actually better/worse. It might only have been better focused. Because of that, more than one test is usually needed.

5.1.3 Focusing using a camera

Because of the problems that still exists with manual focusing another idea was tested. If it would be possible to use a camera to record the image seen in the microscope in real time, then that could be used to focus. By constantly updating the focus and filtering the image to calculate the difference from one pixel to another, it was possible to get a value of how good the focus was. Then this could be used to figure out when there was perfect focus.

5.1.3.1 Problems using a camera to focus

At the first stage a normal web camera was used but the distortions of the image was too large. This made even manual focusing was a lot more exact. Another camera with better contrast as described in section 4.6 ”Cameras” was also tested. However, the distortion in the image was still too large to compete with manual focusing.

This idea could be used to automatically focus if better equipment was available. But since the economy is limited this was not a possibility in this thesis. It could be considered as an option in case the auto focusing system does not work.

5.2 Exposure, developing and etching

The process of producing an image on a Gobo includes exposure, developing and etching. The time of these procedures vary a little and can have an impact on the result of the experiments.

5.2.1 Exposure

When exposing the Gobo the bindings in the photoresist are weakened. This means that when the Gobo is developed the exposure time has a big impact on the result. If the exposure time is too short then it will not have enough energy to dissolve the bindings in the photoresist and everything will be black. If the exposure time is too long then details in the image will disappear and everything will be just white. These are the extremes and will usually not happen very often. Usually an exposure time that is too short will make the fine white details disappear while a too long exposure time will cause fine black details to disappear. Preferably points that are 1x1 pixel should be used and then the exposure time needs to be perfect. However even if it is perfect there might be other things that cause problems and it might not be possible to use such small points as 1x1 pixels.

Something that makes the exposure difficult to determine is that the different intensity in the light source will cause different amounts of time to produce a good result. Also different images will produce a good result with different exposure times. Also an exposure time 10 seconds longer or shorter can be the difference between good and bad results.

5.2.2 Developing

Developing is done to remove the photoresist that does not act as a mask. There are different ways to develop an image as mentioned earlier. However in this project wet developing is used, which means the etching is done by using chemicals. The time it takes to develop is usually around one minute. Compared to exposure, developing does not affect the result so much because a difference in time will not make a big difference. That means this process is stable.

5.2.3 Etching

Etching is the final step of the process and it is done to remove the aluminium layer. The etching time has been a problem because at the start of the project the time used was around 5-8 minutes. However, later in the project longer times were used and in the end a time as long as around 20-30 minutes was used.

Different kind of Gobos were also tested. Instead of the aluminium layer a layer of chrome were used on these. The advantage of chrome layer is that these Gobos are a lot less affected by the etching process. They are however a bit more expensive. Therefore only a few tests were made with these and the result was a bit better at first, but the result was about equal when a longer time was used to etch the normal Gobos.

5.3 Test images

Since the images are sent from a computer, we have total control of the image before it is shown on the display. The problems come after that. But what this means is that if we can find out how the image is affected after it has been sent to the display we can probably modify the input image to correct it. In other words, we send an image to the projector that is distorted in some way to try to remove the errors that is caused in the exposure. To do this a lot of tests must be done first.

5.3.1 Initial tests

The first tests were done with black and white squares looking almost like chess squares. These tests were made with the first light source described in section 4.1.2 ”The light source”. The squares had the sizes 32x32, 16x16, 8x8, 4x4 and 2x2 pixels. Squares with the size 32x32 pixels caused no problems (figure 9), but already at 16x16 pixels the squares were not connected in one direction (figure 10). At 8x8 pixels the squares looked more like circles (figure 11). At lower pixel size than that it no longer looked like squares at all. This result was not very satisfying since we want to use details as small as 1x1 pixels.

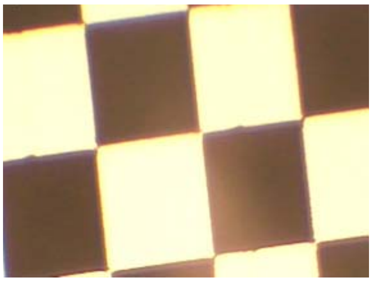

Figure 9: Squares with 32x32 pixels. This looks good even though the corners in one direction are close to not being connected already.

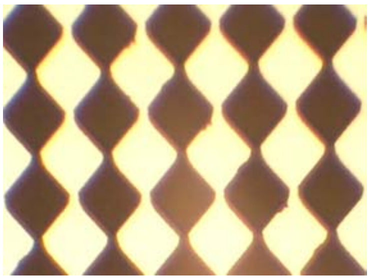

Figure 10: Squares with 16x16 pixels. It is clear that even at 16x16 pixels the image is heavily distorted.

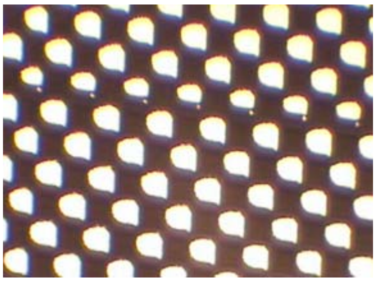

Figure 11: Sqaures with 8x8 pixels. This no longer looks like squares.

Tests using lines were also done. The lines had the sizes 32, 16, 8, 4, 2 and 1 pixel(s). These tests gave a much better result. It was no problem to use lines as small as 1 pixel wide. Tests were done in both vertical and horizontal direction. The results were the same and the conclusion was that lines were a lot easier to use compared to squares (figure 15).

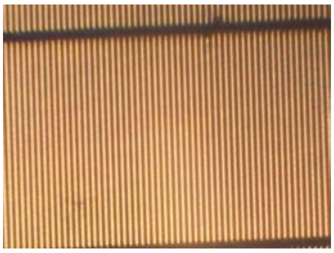

Figure 12: Image showing vertical lines with the width one pixel (5µm). The big horizontal lines are an effect caused by the equipment and will be corrected later.

5.3.2 Grayscale test images

To be able to test the result of grayscales sent to the display in LIOS a grayscale image was created (figure 13). This image was done using MATLAB and it has eight copies of a grayscale ranging from 1 to 255 with steps of two (i.e. 1, 3, 5… 253, 255). This image was then halftoned with different kinds of halftoning. An algorithm was also written that is similar to normal AM-halftoning but with a small difference. Pixels with values close to the threshold but above will not be black. Instead they will be gray and the closer to the threshold they are the lighter the gray color will be. This was also done using MATLAB and the basic code used and later modified can be seen in ”Appendix 1, halftone method using gray scales”. This program can also easily be modified to use line-halftoning instead of AM-halftoning.

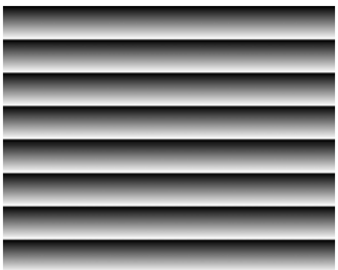

Figure 13: The grayscale image used to test halftoning with grayscales.

5.3.3 Line halftoning with grayscales

Since the tests done earlier assume that lines are easier to use compared to squares, line-halftoning was tested first. The grayscale image in figure 13 was halftoned with the method mentioned in section 5.3.2 ”Grayscale test images” and the image in figure 14 was created. Several tests were then made. The final result was an exposed image that had an almost perfect diagonal line (figure 15). This proved that grayscales could probably be used with line-halftoning at least to improve the image.

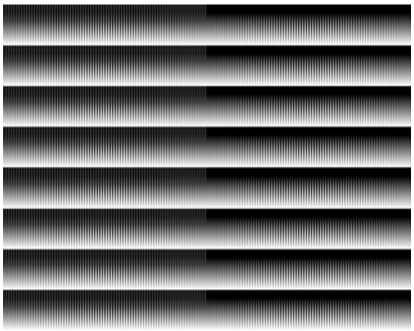

Figure 14: Line halftoning of a grayscale image using the method from appendix 1.

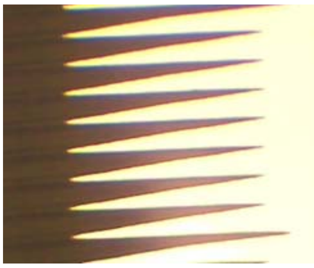

Figure 15: A small part of the result of exposing figure 16. The number of the pixels at the base is 8 and 1 at the top. The grayscales sent to the projector has been exposed very linearly with a nice straight diagonal line.

5.3.4 AM-halftoning with grayscales

The result with line-halftoning was really good but it is always better to be able to use a well-known method that works. Therefore tests using the image in figure 14 were done with AM-halftoning. The code was modified to test different kinds of AM-filters. Some small modifications were also needed to be able to perceive the results better. Half the image was also changed to white pixels on a black background. The reason for this was to test if black pixels on a white background were affected differently from white pixels on a black background. Eight different filters were tested with different shapes and sizes (figure 16). After several tests a somewhat satisfying result was produced (figure 17 and figure 18).

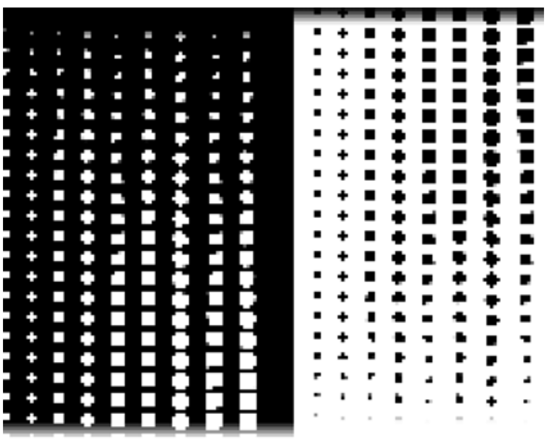

Figure 16: Final test image for AM-halftoning

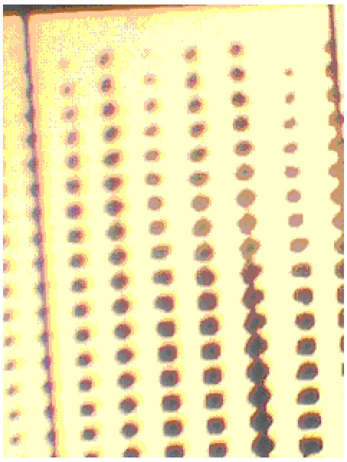

Figure 17: The result of exposing the image in figure 16. This figure shows only the part with black pixels on a white background. This is not as bad as it might first look. The points are getting bigger and bigger when the grayscale increases. Black points with the size 1x1 pixels have mostly disappeared though.

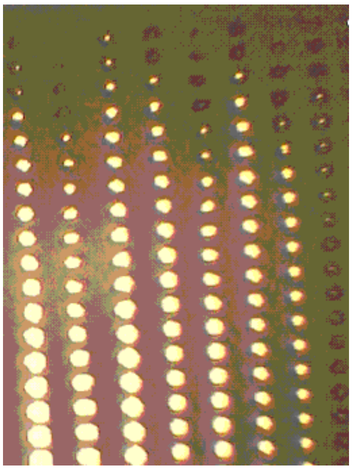

Figure 18: The result of exposing the image in figure 16. This figure shows only the part with white pixels on a black background. This result is a bit worse than the one in figure 17. White points as big as 2x2 pixels have disappeared.

As can be seen when comparing these images the exposure time used in this specific exposure is rather friendly to small black details but unfriendly to small white details. This is a difficult problem to solve. It is possible to change the time so that small black details are kept but small white details disappear and vice versa. This is a balance that needs to be found and that may be different depending on the light source, the input image and size of the points.

5.4 Experimenting with the point spread curve

An important aspect to consider is how the halftoning points are affected by the exposure. More theoretical information about this can be found in section 3.2 ”Dot gain”. However, this task caused several problems that needed to be solved.

5.4.1 The test images

The first test was done using the image shown in figure 19. Before this test was made, it was known that the system had problems, which caused a distortion in the image. The property of this distortion was not known and therefore an image, which had halftoned points in the horizontal direction, was made. This test used points with different sizes varying in range from 1 pixel up to 25 pixels. Since it was known from earlier tests that small black points and small white points were exposed differently both black and white points were tested.

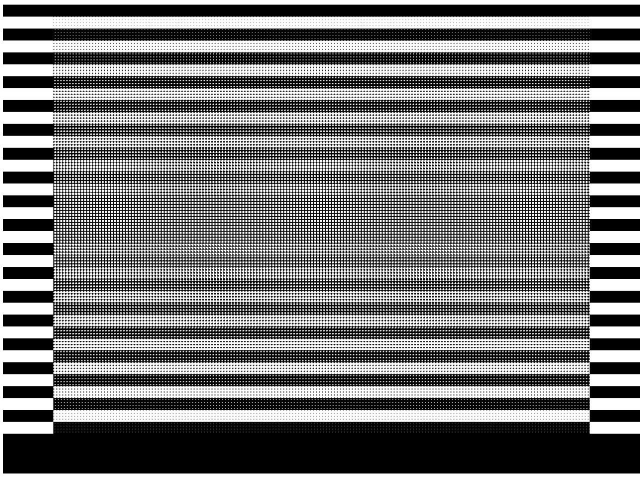

Figure 19: The first test image used to test the point spread curve of the optical system.

The exposure in figure 19 was not good enough either. The result was good in some parts but not consistent enough and another test image was needed. At this time it seemed like the problem was in the vertical direction and therefore a similar image to the one in figure 19 was created but instead of horizontal lines the lines were now placed vertically. The image with vertical lines is shown in figure 20.

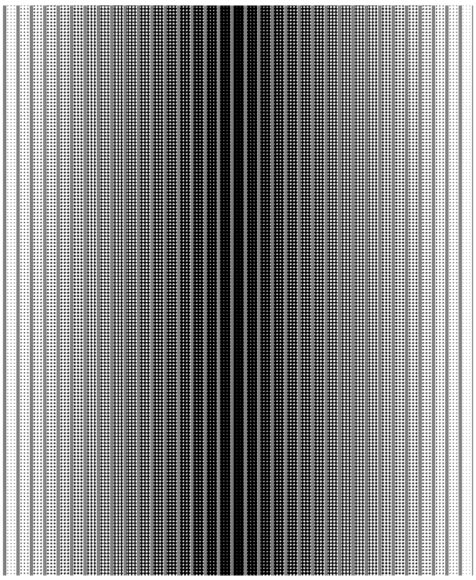

Figure 20: The second test image to test the point spread curve.

Doing this did not solve the problem however and was still not consistent enough to use to draw a point-spread curve. To be able to do that a very consistent result was needed and therefore the size of the points was reduced to 4x4 pixels instead of 5x5 and there were also copies both in the vertical and horizontal direction. Figure 21 shows one enlargement of the image and image 22 shows the whole image.

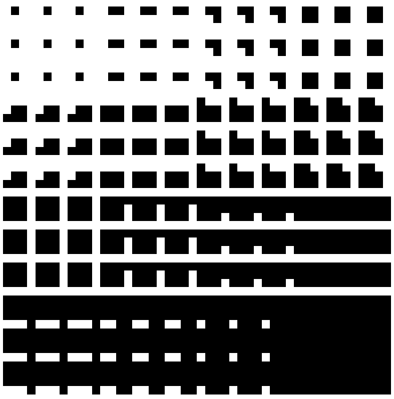

Figure 21: A small part of the final test image. This was good enough to get an exposed Gobo, which could be used to draw the point-spread curve

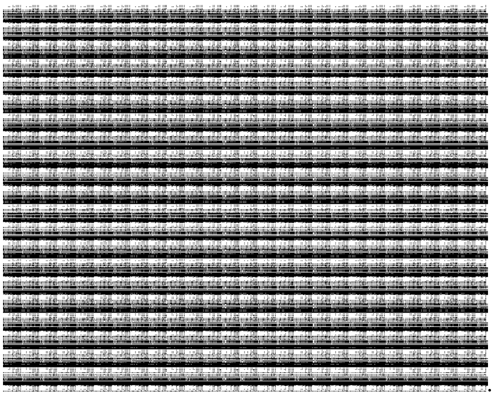

Figure 22: The whole final test image used to draw the point spread curve.

This time the result was still not perfect, but good enough to create a point-spread curve. It is important to point out that the image shown in figure 23 is the best part of the exposure. By using a camera mounted on a microscope it was possible to catch this part of the image on a picture and analyze the image in MATLAB. After cutting out the bad parts the image used looked similar to the one in figure 23.

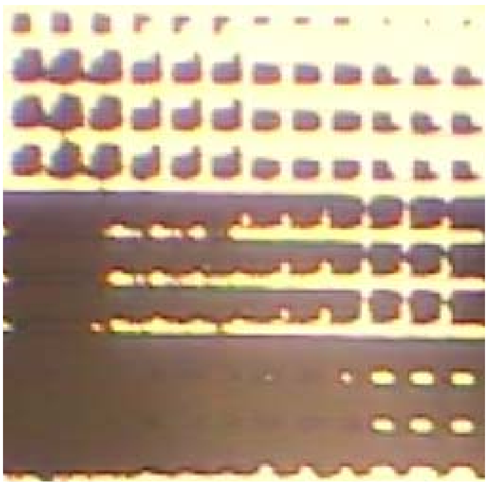

Figure 23: The cut image used to create the point-spread curve.

As can be seen, the picture is still not perfect and some points will most likely look a bit strange. It should however give a good enough test result so it is possible to modify the curve to get a decent result.

5.4.2 The resulting curve

The image in figure 23 resulted in the curve in figure 24. The curve looks a bit strange because four white pixels gives a bigger dot than five pixels. Since this is very unlikely one of the values are most likely wrong. And judging from the image in figure 23 the result that is most likely to be wrong is the point with five pixels.

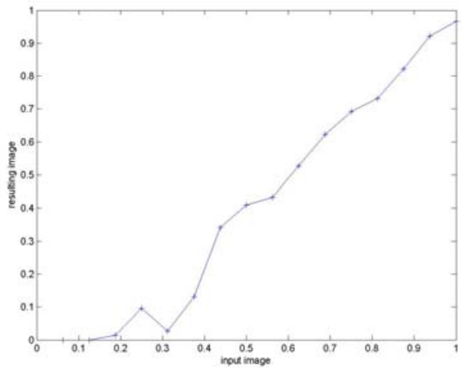

Figure 24: Original curve created from the test values received from figure 23.

Modifying the curve in figure 24 resulted in the curve shown in figure 25. The two values that are probably wrong have been removed and approximated from the rest of the curve. The curve seems to be linear except the part in the start and the end so the values have been approximated using linear estimation.

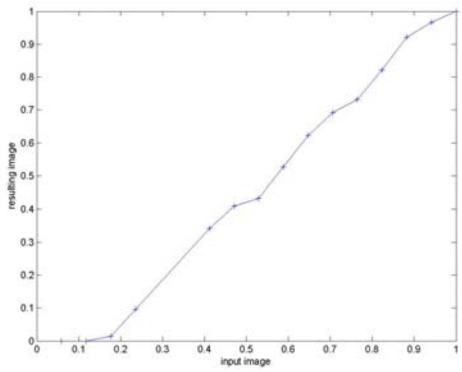

Figure 25: The result after modifying the curve in figure 24. The two values that looked wrong judging from the picture shown in figure 23 has been removed and approximated.

Since the curve looks very similar to a linear curve it was modified further to look like one. This is probably a rather good estimation because the experiment was done using very inaccurate methods and the result still looked rather much like a linear curve. The conclusion is that the curve is rather close the one shown in figure 26. Small black details and small white details will look different when exposed while bigger details will not be affected.

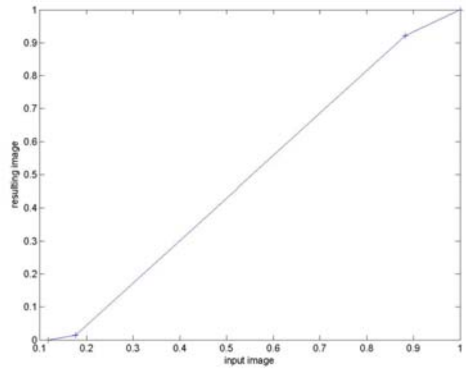

Figure 26: The approximated point spread curve. The experiment as a whole was done using rather inaccurate methods and this is the approximated result.

5.5 Simulations of the exposure

LIOS has been described in detail in earlier parts of the report. However, there are also more technical details about LIOS available. These properties can be used to create a simulation that is an estimation of the exposure. If tests are done to find out more specific details about LIOS, a better simulation can be made which will speed up the project since experiments can actually be done without doing exposures and instead it would be possible to use software. This has the advantages that the experiments will be cheaper and a lot faster. The problem is that the technical details available for LIOS were not sufficient to create a simulation that was close enough to how the real system behaved. After all, the testing was meant to figure out some of these properties and it would require a lot of work to create a simulation that was good enough to use.

A simple program that has a normal Gaussian estimation of the point spread function (PSF) was used in the early parts of the project but later on it was clear that this was not realistic enough. The program used to simulate the exposure can be found in ”Appendix 2, simulation of the exposure”.

6 Developing and testing halftoning

This chapter will describe how the project continued after the properties of the exposure was more or less known. The tests described in this chapter have all been done with the third and last light source described in section 4.1.2 ”The light source”.

A lot of different halftoning methods have been used in this project and what will follow in this chapter are images that shows the result of the different methods and a short comment about the quality of the images. All images have been halftoned using a threshold matrix unless otherwise noted. Very important to notice is that other factors than how the image actually looked before it was exposed can greatly affect the result. Focus and other practical problems might cause errors. The exposed images has been zoomed a bit to better see each pixel. The exposed image is also reversed.

6.1 The test image

Until now, most of the exposures have been done with test patterns and not real images since it is a lot easier to test properties that way. The tests described in this chapter have all been done with an image of musicians. The reason why this image has been chosen is because it is a well-known image and it has a lot of different gray levels.

The image has been cut to be 1280x1024 pixels since that is what the display can handle. Figure 27 shows how the image looked like after it was cut but before any other modifications.

Figure 27: The image used to test halftoning

To be able to see how the exposed image looks like and compare it to the halftoned image an area has been zoomed and it might be interesting to see how that area looked like in the original image also (figure 28).

Figure 28: Original image in the zoomed area, used in this thesis.

6.1.1 Testing IMCDP

IMCDP is one of the best methods available today (figure 29). This means that if it would be possible to expose an image using IMCDP it would most likely not be necessary to test normal FM or AM halftoning since IMCDP would give better results.

Figure 29: The image has been halftoned using IMCDP.

The zoomed area looks like in figure 30.

Figure 30: The zoomed area after using IMCDP. This is a zoomed area of figure 29.

Exposing this image gave a rather bad result (figure 31).

Figure 31: The result of exposing the image shown in figure 29. Compare with figure 30.

There are big areas where the halftoning is totally gone, this especially occurs in the big white areas and the big black areas. It is rather obvious that this image will be too difficult to expose because of this.

6.1.2 Testing FM halftoning

The testing showed that exposing small details was very difficult. FM halftoning has just as small details as IMCDP and because of that FM halftoning has not been tested.

6.1.3 Testing AM halftoning

IMCDP did not give a satisfying result so something with fewer small details was needed. Therefore AM halftoning was tested. However, normal halftoning also has details that are rather small, which caused problems in the brightest and darkest areas. But it is a lot easier to change the minimum size of the dot depending on how the threshold matrix looks like. The first test was done using a normal AM threshold matrix but the result of it was rather bad and a modified threshold matrix was used instead (figure 32).

Figure 32: A modified AM halftoning using a threshold matrix.

And the zoomed area can be seen in figure 33.

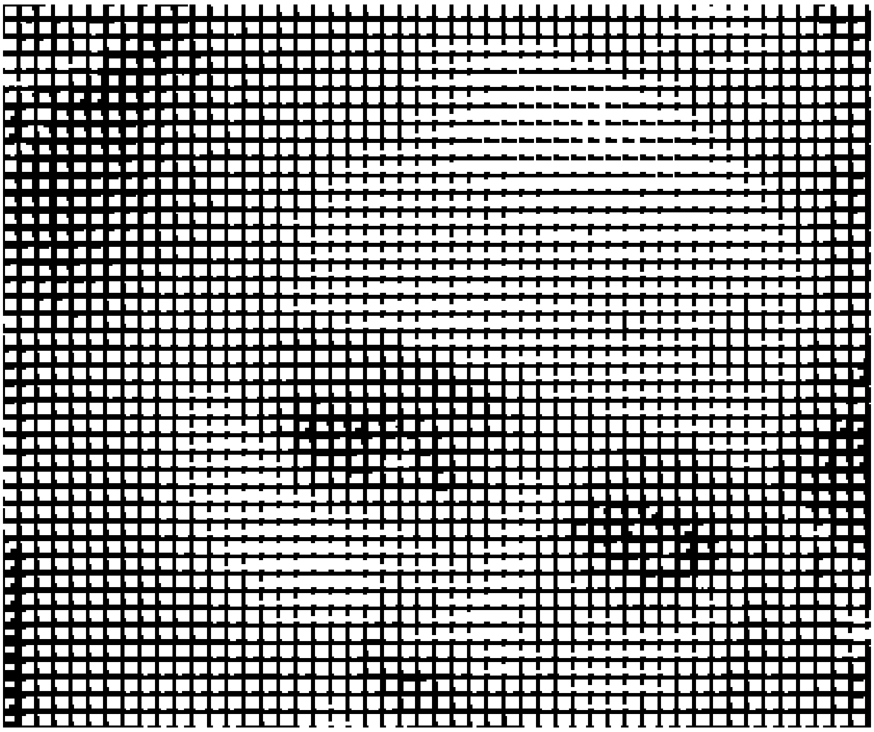

Figure 33: The zoomed area after using modified AM-halftoning.

The smallest black dots are 2 pixels and the next size of black dots is 4 pixels. The smallest white dots are 4 pixels. A 6x6 matrix has been used. Exposing this image did not really give a satisfying result either (figure 34).

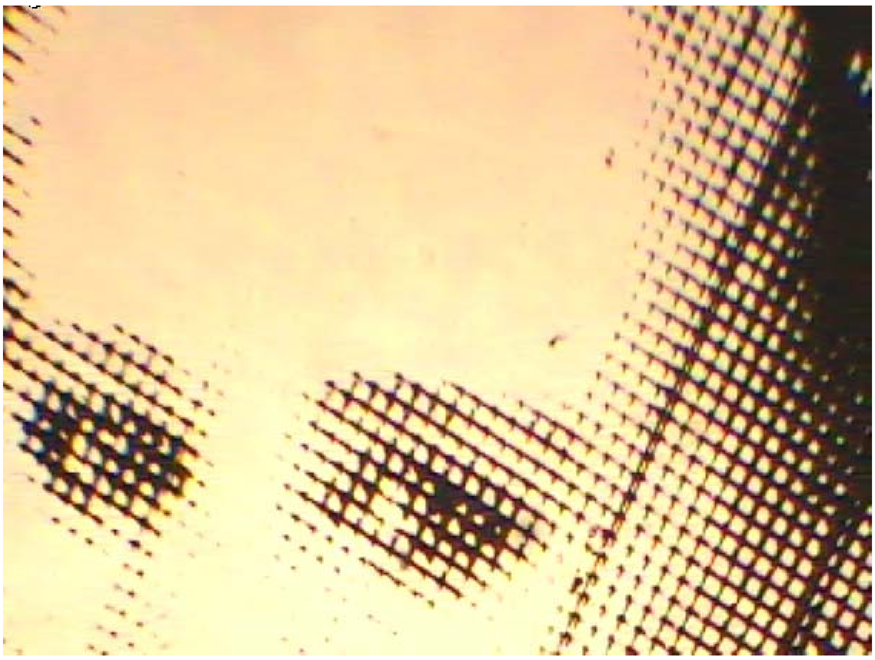

Figure 34: The result of exposing the image shown in figure 32. Compare with figure 33.

The area where the halftoning disappears is a bit smaller compared to IMCDP, especially in the darker areas. This exposure looks very good in many of the darker parts but the big white area at the forehead has still lost the halftoning dots.

6.1.4 Line halftoning

The first part of the project showed that lines would probably be easier to expose compared to squares. Because of that and the fact that AM halftoning did not give a satisfying result, line halftoning was tested (figure 35).

Figure 35: The result of line halftoning the image shown in figure 26.

The zoomed area can bee seen in figure 36.

Figure 36: The zoomed area after using line-halftoning.

It is a lot easier to actually notice that this is a halftoned image compared to the earlier halftoned images even from a long distance. This is a direct result of using line halftoning. The matrix used here is a 4x1 matrix and it only has 4 gray scales. The result of this exposure was rather disappointing however (figure 33).

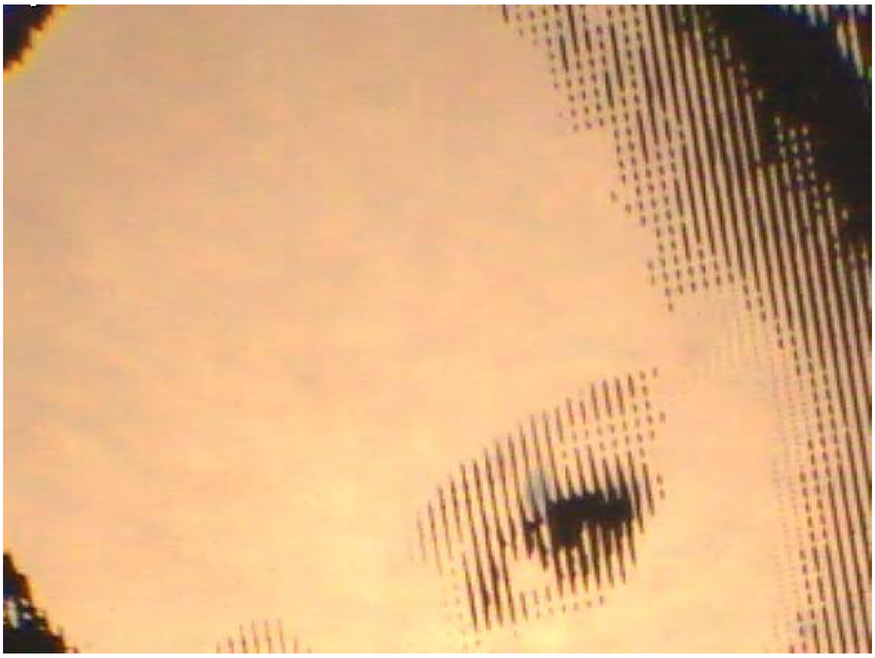

Figure 37: The result of exposing the image shown in figure 35. Compare with figure 36.

The image is very bad and a reason might be bad focus. The dots are still disappearing in the darkest and brightest areas.

6.1.4.1 Testing different threshold matrices for line halftoning

Just as with the threshold matrix for AM halftoning it is possible to adjust the threshold matrix for line halftoning. This has been done and the minimum line width in the threshold matrix has been changed to two pixels instead of one (figure 38).

Figure 38: Line filter with 2 pixels width.

The zoomed area can bee seen in figure 39.

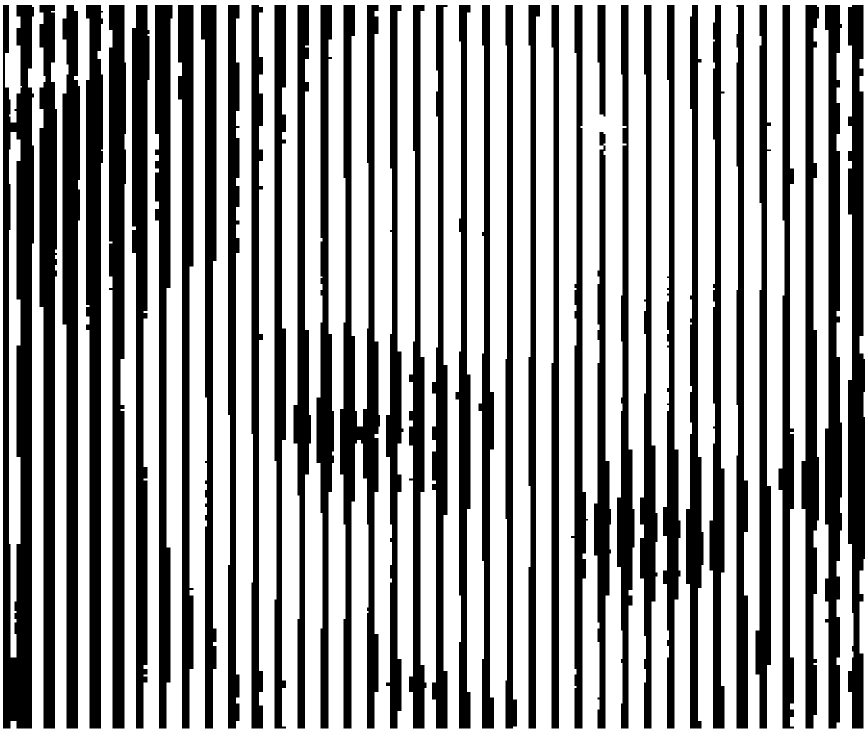

Figure 39: The zoomed area after using line-halftoning with 2 pixels width.

Here a matrix with size 8x1 has been used. The smallest black and white lines are two pixels instead of one pixel and the number of gray levels is 6. Exposing this image gave a result that was a bit better (figure 40).

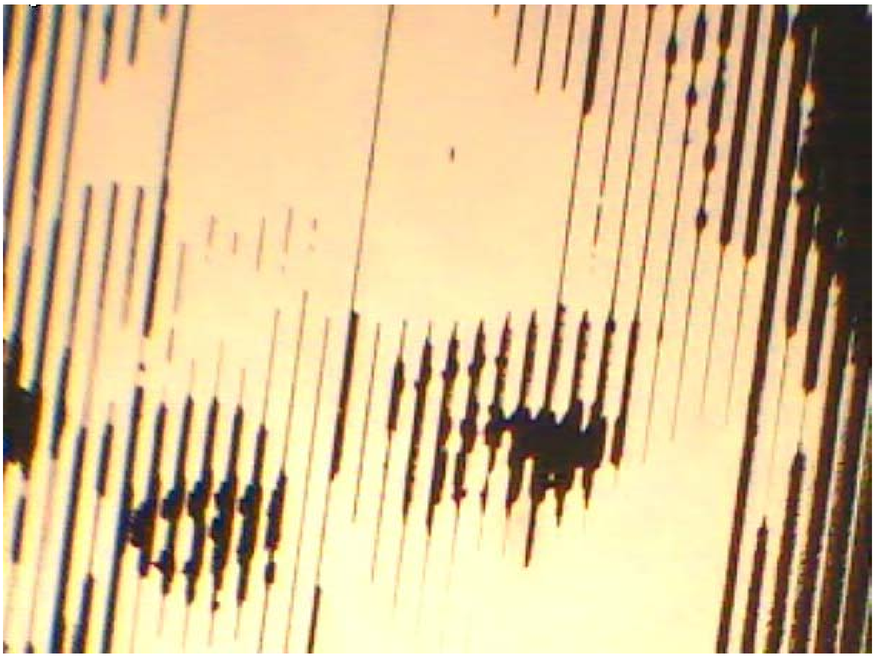

Figure 40: The result of exposing the image shown in figure 38. Compare with figure 39.

Still, big parts of the brightest and darkest areas are missing. The parts missing are significantly smaller however. Overall this image looks ok but it is still possible to make improvements.

6.1.5 Using Error diffusion

As explained in section 3.1.5 ”Error diffusion” an image that is halftoned always has an error and by spreading this error and correct some of it the overall quality of the image can usually be improved. Line halftoning is a rather bad method to use and if it is possible; a method to improve the image should be used. A good way to do this is to use error diffusion.

6.1.5.1 Using error diffusion in AM halftoning

AM halftoning was too difficult to expose but it would be a lot better to use compared to line halftoning. Therefore error diffusion in AM halftoning was tested first. However, since the threshold matrices used already had 25-36 gray levels it did not really make such a big difference on the quality of the image. Because of that it was never exposed. Besides, using error diffusion in line halftoning showed that the image was actually more difficult to expose after using it.

6.1.5.2 Using error diffusion in line halftoning

There is no public method to use error diffusion in line halftoning so one had to be created. A program was written to achieve this and it is in no way optimized to achieve the best possible result. The main reason for this is the time it would take and another reason is that it will probably make the image more difficult to expose. Even though the method is not optimized it still made a significant difference on the visual appearance of the image. The program used can be seen in ”Appendix 3, error diffusion in line halftoning”. Tests were done using the same matrix that was used in the image in figure 38 but with error diffusion added (figure 41).

Figure 41: Line halftoning with error diffusion.

The zoomed area can be seen in figure 42.

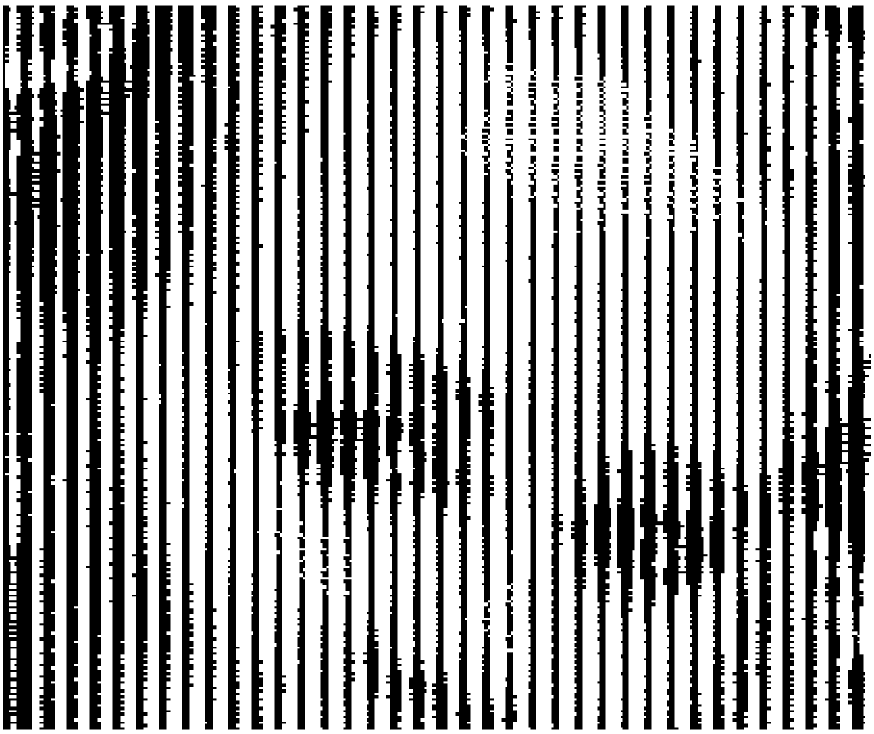

Figure 42: The zoomed area after using line-halftoning with 2 pixels width and error diffusion.

This image looks a bit better compared to the one without error diffusion (figure 38). Zooming in on different areas in the image shows that it has smaller details so it will probably be more difficult to expose it. Exposing it however gave a rather good result in most areas, however it still is not perfect in the areas with small details (figure 43).

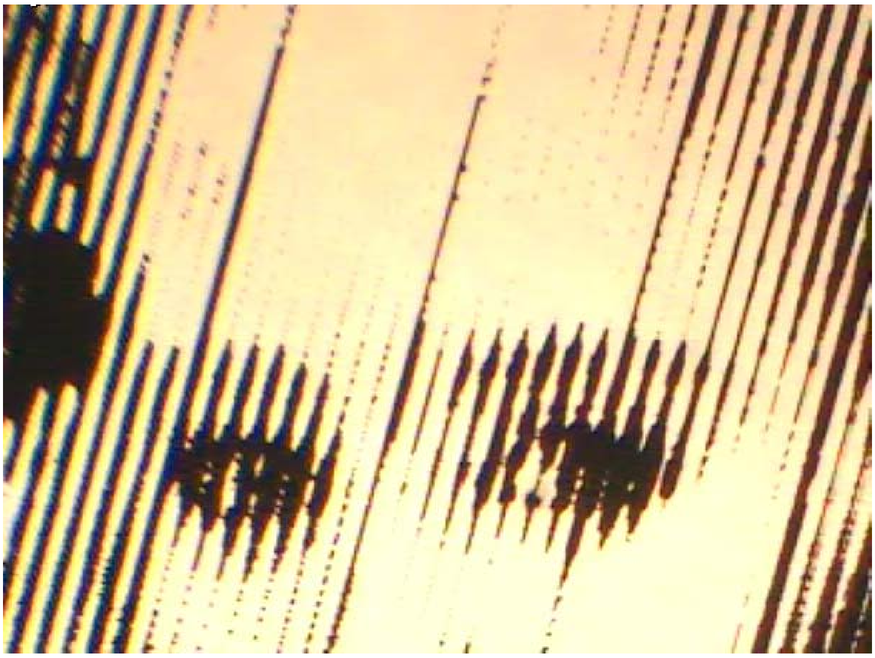

Figure 43: The result of exposing the image shown in figure 38. Compare with figure 39.

Using error diffusion made the image look better before exposing, but error diffusion made some of the dots smaller than before. Because of that more details disappeared in the exposure compared to the image without error diffusion.

6.1.6 Using known properties to modify the image

The main problem has been exposing small details, especially small white details. If the image can be modified to compensate for this, it might be possible to expose an image of higher quality like AM halftoning instead of line halftoning. The time remaining for the thesis was now limited. Therefore the testing of this has also been limited and it is an area where more work would probably be useful. The program used can be seen in ”Appendix 4, a program to make exposing easier”.

What the program does is basically to search for the brightest and darkest areas in the picture. Then, if the image is very dark in one area the darkest parts in that area is set to a gray level depending on the mean brightness in the area. If the area is very bright the brightest parts is instead set to a gray level. Since small white details are more difficult to successfully expose this has also been compensated for, which means the mean of the image is slightly brighter after the compensation.

First it was tested on the image that was halftoned with line halftoning with 2 pixels width and with error diffusion. Doing this made a significant improvement. Because of this it was also tested on the image with the modified AM halftoning in figure 32 (figure 44).

Figure 44: AM halftoning with error diffusion, modified to be easier to expose. The modification is especially noticeable in the white areas.

The zoomed area is shown in figure 45.

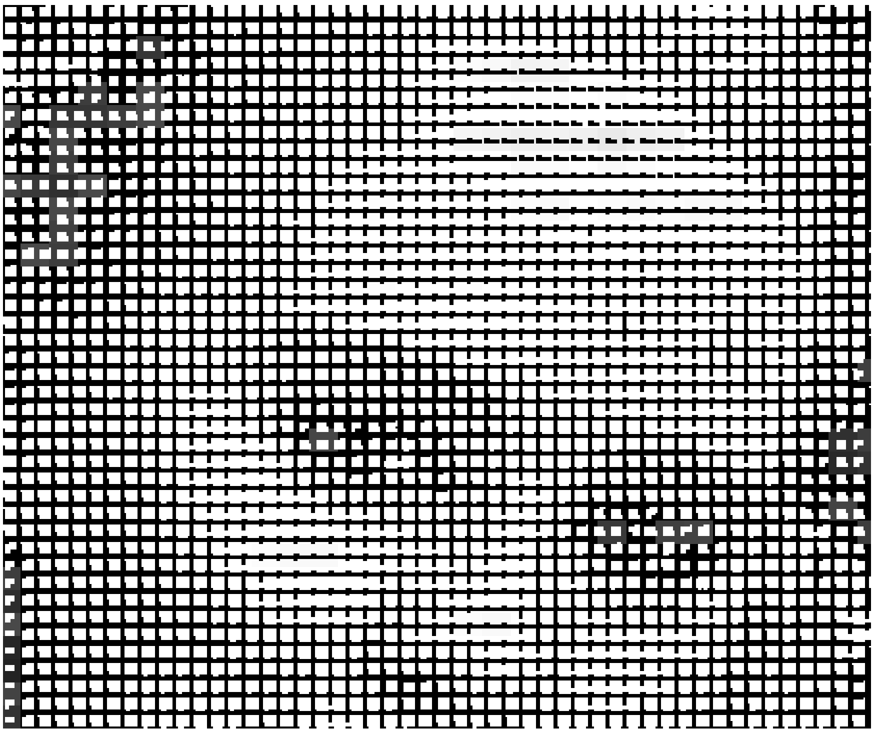

Figure 45: The zoomed area after using a modified AM threshold matrix and modifying the darkest and brightest areas. The modification can easily be seen in the gray areas in the forehead.

The reason why grayscales could be used at all is because LIOS can handle gray levels, which cannot be handled in normal halftoning. Even though the image becomes binary after the etching process it is still possible to use the gray levels in LIOS to modify the image before it is exposed.

The first tests were made with the modified line halftoning with error diffusion. This showed that modifying the image in this way actually made it easier to expose. Since AM halftoning would be better, a modified version of AM halftoning was exposed (figure 46).

Figure 46: The result of exposing the image shown in figure 44. Compare with figure 45.

The smallest dots in this image are around 10 µm.

As you can see all dots are now visible even after the exposure. The other parts of the image also show very good results. This exposure is close to perfect except in the darkest areas where there is still a small problem with small white dots disappearing.

6.2 Testing with chrome Gobos

At the end of the project a new possibility appeared. The etching could maybe be a problem in the process and because of that chrome Gobos was also tested. As described in section 4.3 ”Special chrome Gobos” are a lot easier to etch compared to normal Gobos.

A few tests were made and the result with the chrome Gobos looked better at first, but using a longer time to etch the normal Gobos gave the same result. Since the Gobos with aluminium layer is cheaper they were used instead even though the etching time is longer.

7 Conclusions

7.1 Properties of the exposure

At the start of this project the properties of the exposure was close to totally unknown. The main reason for trying to use LIOS was to remove the step of using a mask when producing Gobos. However, it was not known if the direct exposure would prove good enough to actually be possible to use in the production line. The experiments that have been done have proved that it will most likely be possible to do so. If the quality of the image will be better or worse than today and how much work that needs to be done before direct exposure can be used in the industry remains to see. The tests assume that if some more work is put into this, the quality will most likely be better than what is possible to achieve today.

The qualities of LIOS or the equipment connected to it will likely change in the close future since some parts of the equipment is not good enough. Then it will be important to make new tests to know how the changes affected the exposure. The property of the exposure today has been heavily tested and a method to fit them has been made. Unless the modification makes the exposure more difficult the method developed in this project will most likely be good enough. To use LIOS to its maximum potential and create images of the best possible quality the method will probably have to be modified.

7.1.1 The light source

The current light source has two main problems. The first is that a significant part of the image remains black after exposure. This problem appeared the first time when the current light source was tested why the problem most likely is caused by the last light source. The second problem is the time of the exposure. The latest test has been with a time around 14-15 minutes. Since there must be several exposures to cover the whole Gobo the time is too long. The exposure time is supposed to be as short as around 1 second, which is a huge difference from 14-15 minutes. These two problems must be fixed, why a new lightsource will be needed. This will change the properties of the system and hopefully this would not mean that it will become more difficult to expose small details. This could even make exposing small details easier.

7.1.2 The display in LIOS

A lot of the problems experienced today are the result of a contrast that is not good enough. Getting a better contrast would have the following advantages:

- Focusing would not have to be as exact as it is today.
- It would be possible to have an exposure time long enough to make sure all pixels are exposed. This is not possible today because if the time used is too long it means that the small black details disappear. This might be very important since the exposure time is supposed to be one second. With this short time and the display used today it will be very important to make the exposure time very exact or it will affect the quality of the exposure.
- It would most likely be possible to use a halftoning method that results in better images. This will greatly improve the quality of the image on the exposed Gobo. A good enough contrast will even make it possible to use the gray levels in LIOS for something better than removing some of the distortion.

As you can see there are advantages for a new display, but today CRL Opto, which is the company that produces the display, consider it is too expensive to produce a display with a better contrast. The reason is that the display is optimized for green light with a frequency of 550 nm. The optical system in LIOS is however optimized for blue light with a frequency of around 405 nm. To create a display optimized for another frequency CRL Opto has to change their production to that frequency instead. Since photoresist sensitive for green light doesn't exist, it isn't possible to modify LIOS instead of the display.

7.2 Etching

The etching time was not believed to cause any big problems at first, but changing the time of the exposure proved that it did indeed affect the result. By trying a longer and longer etching time the result got better and better. Testing also showed that having a longer etching time did not have any negative effects on the result. On the opposite side a longer time did actually bring out the smaller white dots while still preserving the smaller black dots.

In the beginning an etching time of around 5-8 minutes was used because it was believed to be enough. At the end the time was around 20-30 minutes. Worth mentioning is that the etching is an acid that probably became weaker as more exposures was done but it did most likely not become so much weaker that the time increased fourfold. The Gobos with a chrome layer, which are easier to etch, did not really make any bigger difference compared to a longer etching time for normal Gobos. The tests done with these were very limited since chrome Gobos are more expensive and it did not seem like they gave a better result.

7.3 Focusing

A lot of work has been put into creating a good way to focus. The thesis done by Ida Nordvall [6] theoretically showed that using the same way to focus as for CD-ROMs would be possible. The problem is that even though it should work theoretically it did not work in the reality depending on weak reflection.

A lot of work was put into the project trying to focus using a camera recorded the image in a microscope. This way is not accurate enough, at least not with the equipment that was available for this project. Even manual focusing was more accurate but it is worth considering using this technique in case it would prove too difficult to use the astigmatic method.

7.4 Simulations

Simulating would have had three main advantages compared to using practical experiments:

- The time for each exposure would decrease a lot. The time to simulate an exposure would probably be less than one minute on a modern PC compared to more than one hour for practical experiments.
- It would be significantly cheaper to use a simulation. Both since it would take less time but also because no Gobos or chemicals would be used.
- The parameters would not change between every exposure. It would be possible to keep all parameters constant while only changing one of them at a time for testing that variable. The way it was done in this thesis was to change one variable and trying to keep the rest stable at the same value. This made it a lot harder to actually know if the changed variable was the reason for a better or worser result or if there were other reasons, like better focus.

If an optimal process is going to be done with the best quality possible, it is most likely necessary to find out all the properties of the exposure to make it possible to create a simulation. Using only practical experiments will be too time consuming and costly.

7.5 The resulting halftoning method

The result of this project is a halftoning method that uses an AM threshold matrix (figure 46). This is a well-known method that has been used for long time. It is easy to use, fast and stable. If it is possible to change some details in LIOS to make it easier to expose, then another method could be used: IMCDP, FM with error diffusion or a hybrid AM/FM will all create a better image than AM. Even a threshold matrix that uses smaller dots as minimum size will probably give better quality even though not as much as the before mentioned methods.

The method to use gray levels in LIOS to adjust the image could also be modified. If it would be possible to use dots smaller than the current pixel size in LIOS it would be possible to use gray levels to create images of really high halftoning quality if a special method was created to do this. The result would be a halftoning method that could be even better than any of the existing methods today. The reason is that it would be possible to use more gray levels without making the halftoning dots bigger. This will result in an image where the halftoning dots are less visual than today, thus increasing the visual quality of the image. The gray levels have been used to fix some of the distortions with great success. This would still be useful if another halftoning method would be used, because the modification of the image is done after the halftoning has been processed. This makes it possible to remove some distortions independent of the method used even though the method created in this thesis works best with AM halftoning.

8 Future work

A lot of work still has to be done before direct exposure can be used in the industry. Even though a lot of testing has been done, some more could probably yield a halftoning method that is marginally better even though the one developed most likely is good enough. Spending time in other areas will probably be more efficient.

8.1 Improving equipment

The equipment used must be improved. With the current setup the exposure only covers a part of the image and the rest is just black. The reason for this is most likely the light source and a better one would probably solve this problem. A better display would also be very useful. As mentioned earlier this will also mean that the properties must be tested again.

8.2 Focusing

Something must be done about the problem with focusing. It might be possible to use some kind of manual focusing if a display with better contrast is produced. If this is not done however, auto focusing will most likely be necessary to be able to use LIOS to produce Gobos at all. Without it, the quality of the exposure will be too bad.

8.3 Position logic

To be able to cover the whole Gobo the image needs to be divided into many small parts. This means that first some kind of program is needed to divide the image into these small parts. When this is done the Gobo has to be moved with extremely good precision to avoid errors because the edges overlap too much. The edges of the images probably need to be smothed so the images can overlap slightly.

8.4 Simulations

To simplify the exposures it would be very helpful if a simulation of the exposure could be developed. This would mean the process of creating a better method to expose would be quicker and easier. The problem to create a simulation is that a lot of tests have to be done first to find out all properties, properties that could change from time to time.

8.5 Another halftoning method

If a better equipment is used this will probably make exposing less sensitive to small details. That means it will be possible to use another halftoning method to create an image of higher quality before and, hopefully after, it is exposed. It will also most likely be possible to use the gray levels in LIOS in another way when the exposure is more stable.

9 References

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10 Appendix

10.1 Appendix 1, halftone method using gray scales

```
% halftoneimage = htgray(grayimage)
%
% Converts a grayscale image to a halftoned image with a grayscale
% interpolation for the single pixel that is on the threshold.
%
% Author: Stefan Gustavson (stegu@itn.liu.se), 2004-09-17
% This is experimental code, not guaranteed to do anything useful.

function himg = htgray(gimg)

% Create threshold matrix with a spiral AM dot pattern
% t = [15 14 13 12; 4 3 2 11; 5 0 1 10; 6, 7, 8, 9] + 1;
% Create threshold matrix with a line screen pattern
t = [3 2 1 0 0 1 2 3] + 1;
[th,tw]=size(t);
tmax = max(max(t))+1;

% Replicate the threshold matrix to the same size as the input image
[h,w]=size(gimg);
timg = repmat(t, fix(h/th)+1, fix(w/tw)+1);
timg = timg(1:h, 1:w);

% Threshold the grayscale image to get the black and white pixels, but
% keep grayscale information for the pixel that is on the threshold.
% That single gray edge pixel is what makes this into something else
% than a regular halftoning. (Not sure if it is any *better*, though.)
dimg = (gimg*tmax - timg);
himg = (dimg > 0); % The regular thresholding, to only black and white
himg = double(himg); % Convert to numbers from the boolean (0/1) class
idx = find((dimg > 0) & (dimg <= 1)); % This is the borderline pixel
himg(idx) = dimg(idx); % Make it show how far from the threshold it is

% Done!
```

10.2 Appendix 2, simulation of the exposure

```
% simgobo.m
%
% Matlab script to simulate a lithographic imaging system.
%
% The input image is up sampled to 8x its original resolution,
% convolved with a point spread function (PSF) and threshold
% to simulate the photoresist exposure and subsequent etching
% in a reasonably realistic manner.
% Options of adding some noise are given, but commented out.
% Note that the PSF is chosen completely arbitrarily.
% A proper simulation should use a PSF with a connection
% to reality - calculated, measured or at least estimated.
%
% This script requires the Image Processing Toolbox to run.
% Author: Stefan Gustavson (stegu@itn.liu.se) 2004-09-13

% The input image. Use a very small one, just to demonstrate the principle.
% A more useful simulation would read this from a file with 'imread().'
lcd = [0 0 0 0 0; 0 0.7 1 1 0; 0 0.5 1 0 0;  0 0.3 1 1 0; 0 0 0 0 0];

% If LCD image plate noise or irregularities in light field intensity
% should be simulated, do that here by adding noise to 'lcd',
% and/or perform a point by point multiplication with a maximum
% intensity image of the same size.
% lcd = lcd + some_noise_image;
% and/or: lcd = lcd .* max_intensity;

% Resize the input image to 8 times its original size,
% using nearest neigbor interpolation to get 8x8 pixel blocks.
% If the input image is large, this will be a *very* big image,
% so think twice before you try to simulate a 1280x1024 image
% or something. With lots of memory, it can be done, but it
% will take ages to do the convolution in the next step.
% If you realy want to simulate a full size image, it is
% advisable to split it into reasonably small pieces first.
lcdbig = imresize(lcd, 8, 'nearest');

% Guess a PSF. This is a Gaussian profile, a few pixels wide.
x = ones(15,1)*(-7:7);
y = x';
psf=exp(-0.04*(x.*x + y.*y));
% Normalize the PSF to have unit energy, i.e. sum(sum(psf))==1
psf = psf/sum(sum(psf));

% Convolve the upsampled input image with the PSF.
exposure = conv2(lcdbig, psf, 'same');
```

```
% If image noise and exposure sensitivity noise should be added,
% do that here by adding noise to 'exposure'.

% Threshold and invert the exposure to make a binary pattern.
% The threshold might not be exactly at 0.5 in the real system.
% It depends on material properties and the exposure time.

out = not(exposure > 0.5);

% Make a version that has some noise, just to demonstrate its effect
noise = randn(size(exposure)); % Normal distribution
noise = conv2(noise,[1 2 1; 2 4 2; 1 2 1]/12,'same'); % Low pass filter
exposurenoisy = exposure + noise*0.1;
outnoisy = not(exposurenoisy > 0.5); % Threshold

% Done!
% Show the input, the intermediate steps and the end result side by side
imshow([lcdbig, exposure, out, noise, outnoisy]);
```

10.3 Appendix 3, error diffusion in line halftoning

```
% Line halftoning with error diffusion

% Author: Daniel Nilsson (danni931@itn.liu.se), 2005-01-19

gray_img = imread('w:\examensarbete\testimages\musicians\musicians-gray.png'); % read the
input image
gray_img = double(gray_img(1:1024+10, 1:1280+10))/255; % cut the image to the right size
and convert into double, use a few extra pixels

% thresh_matrix = [7 5 3 1 2 4 6 8]; % threshold matrix with linescreen pattern
% thresh_matrix = [5 3 1 2 4 6]; % threshold matrix with linescreen pattern
% thresh_matrix = [3 1 2 4]; % threshold matrix with linescreen pattern
thresh_matrix = [6 4 2 1 1 3 5 6];
% thresh_matrix = [5 3 1 2 4];
[thresh_height, thresh_width] = size(thresh_matrix); % get the size of the threshold matrix
thresh_max = max(max(thresh_matrix))+1; % get the highest number in the threshold matrix

% set the size of the image
img_height = 1024;
img_width = 1280;

error2 = 0; %test
% the error diffusion
for x = 1:thresh_width:img_width
  for y = 1:thresh_height:img_height
    line_img = (gray_img(y:y, x:x+thresh_width-1)*thresh_max - thresh_matrix); % normal
thresholding
    ht_img(y:y, x:x+thresh_width-1) = (line_img > 0); % The regular thresholding, to only
black and white
    error = sum(gray_img(y:y, x:x+thresh_width-1)) - sum(ht_img(y:y, x:x+thresh_width-
1)); % calc the error
    error = error/thresh_width; % error for each pixel
    error2 = error2 + error; % test

    if y < img_height % ouside matrix dim at the last line
      gray_img(y+1, x:x+thresh_width-1) = gray_img(y+1, x:x+thresh_width-1) + error; %
Spread the error into the next line
    end
  end
end

ht_img = double(ht_img(1:img_height, 1:img_width)); % Convert to numbers from booleans
(0/1)

figure;
imshow (ht_img);
```

10.4 Appendix 4, a program to make exposing easier

```
% Modify the input image to (maybe) lose fewer details when exposing.

% Author: Daniel Nilsson (danni931@itn.liu.se), 2005-01-24

function mod_image = exposure(ht_image)
% ht_image = double(ht_image(1:1024, 1:1280))/255; % cut the image to the right size and
convert into double
mod_image = ht_image; % create a copy of image to prevent distorting the original

% figure (1);
% imshow(ht_image);

for y = 1:8:1024
   for x = 1:10:1280
      img_mean = sum(sum(ht_image(y:y+8-1, x:x+10-1)))/(8*10);
      if img_mean < 0.3
         mod_image(y:y+8-1, x:x+10-1) = mod_image(y:y+8-1, x:x+10-1) * (1 - img_mean) +
(img_mean); % preserve ones and limit min
      end

      if img_mean > 0.8
         mod_image(y:y+8-1, x:x+10-1) = mod_image(y:y+8-1, x:x+10-1) * (1.8 - img_mean);
% preserve ones and limit min
      end
   end
end

% figure (2);
% imshow(mod_image);

% imwrite(mod_image, 'w:\examensarbete\testimages\line_ht_1x8_ed2_gray.png');
```