Measurement Light Bulb

EE3L11

Electrical Engineering Bachelor Thesis

Subgroup:
Light source and camera synchronization

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July 21, 2019

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Abstract

This document describes the design process the prototype of a measurement light bulb which is able to project spherical harmonics of orders 0-1-2. Photographs of these projections can be combined to represent many light distributions. The measurement light bulb can be used in the field of research focused on the computation of the illumination impact of lighting, more specifically, simulating different light sources. Our prototype consists of a laser beam rotating over two axes, which allows the device to project onto a sphere around itself. The device can be controlled wirelessly using Bluetooth.

The lamp can project spherical harmonics in a resolution of $4°$ and 256 monochrome light levels. The time one projection takes is about one second, which allows for quick measurements. The dimensions and the weight of the lamp are such that it is portable. At this stage, the prototype can only operate in a dark environment, due to the use of a low powered laser.

In this document, the focus will be on the light source, its corresponding drivers and the camera synchronisation.

Preface

We would like to wholeheartedly thank everyone involved in this project.

Our supervisors Elmar Eisemann, Markus Billeter and Nestor Salamon for giving excellent guidance during this project. They were always compassionate to us and brought excellent knowledge to the table. They also delivered very helpful advice regarding the writing of our theses.

Ioan Lager also receives our gratitude for organising the bachelor graduation project and keeping things on track.

Another person we would like to thank is Jianning Dong, who gave us advice regarding motors and their corresponding controllers.

We would also like to thank the Intelligent Systems Department for letting us use their cluster computer, which allowed us to run a heavy optimisation algorithm for pattern calculations, and letting us use their 3D printer, which allowed us to easily produce custom parts.

Lastly we would like to thank Martin Schumacher for being supportive of our project and his dedication to make sure all our components were delivered in time.

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Chapter 1

Introduction

Almost nothing is as much part of our everyday life as light. It is therefore no surprise that light can have a large impact on us: correct lighting can set the right mood and is thus also an important element in interior design. Designing a room requires knowledge of how the room is to be lit, what it is going to look like and how this influences the people inside. Simulating lighting plays a big part in this. Computer programs have been developed specifically for this purpose. However, simulating light, either from a lamp or from the sun, turns out to be hard, since the way it spreads across a room depends on a large number of factors, a lot of which are unknown. Due to this, computer simulation is very costly and difficult to control. This is where our project comes in.

Instead of simulating lamps via computer programs, we opt for a simulation with a physical measurement light bulb. This measurement light bulb has been built to project a finite set of special light patterns: spherical harmonics (SHs), which can be combined to represent many light distributions.

The principle is to capture the device's illumination impact from a given point in the room with the aid of a camera. The photos, resulting from capturing several spherical harmonics projections from the measurement light bulb, can be combined in a post-process to yield the result that would have been obtained by a different light source placed at the same location. For any light source, a specific combination of SHs coefficients exist so that their weighted linear combination yields an approximation of the light's emission pattern. In consequence, by combining the photos using the same coefficients, we can predict the illumination of the given light source. The resulting technique is a lot more efficient than simulating all reflections of the room.

When the light bulb is able to project high resolution SHs and the reflectance properties can be captured, many sorts of light sources could be simulated. Hereby, our work can become a useful tool for interior designers to simulate lighting in a room, or even an entire building. It is possible to have a preview of the results of lamp arrangements without physically installing these. Hereby, the user saves a lot of time and as the capture is only performed once, it enables the exploration of many design options in a post-process.

In this chapter, some prerequisite knowledge about spherical harmonics will first be discusses. This is followed by a brief overview of some related work. After this, the problem definition is laid out. Next come the criteria for the prototype, an overview of the project dynamics and lastly an outline of the entire thesis.

1.1 Prerequisite knowledge about spherical harmonics

As indicated in the introduction, the idea of our solution is to approximate the light emission pattern of a light source using spherical harmonics and rely on our measurement light bulb to actually emit the spherical harmonics pattern into the scene. In order to provide a better understanding, we will first briefly revisit spherical harmonics.

Spherical harmonics are a set of orthogonal basis functions over a sphere. In principle, they can be thought of as the equivalent of a Fourier basis on a spherical surface. In consequence, they can be used to represent various spherical functions by projecting the function into their spherical harmonics basis.

The higher the order of the basis, the more accurate the representation of the function becomes (similar to adding frequencies for the Fourier case).

The general equation for complex spherical harmonics is given in Equation 1.1. However, since complex light cannot be projected, they are transformed to form a real basis.

$$Y_l^m(\theta, \phi) = Ne^{im\phi} P_l^m(cos(\theta)) \tag{1.1}$$

In Equation 1.1, l is the order and m is the index of the spherical harmonic function Y, N is the normalisation constant and P is the Legendre polynomial. ϕ is the longitude and θ the colatitude of the sphere as can be seen in Figure 3.2.

In our work, we will focus on a lower dimensional SH space up to order two (as illustrated in Figure 1.1). In the future, higher order representations could be added, but it has been shown that the first three bands can be used to make very accurate representations [Ramamoorthi and Hanrahan, 2001].

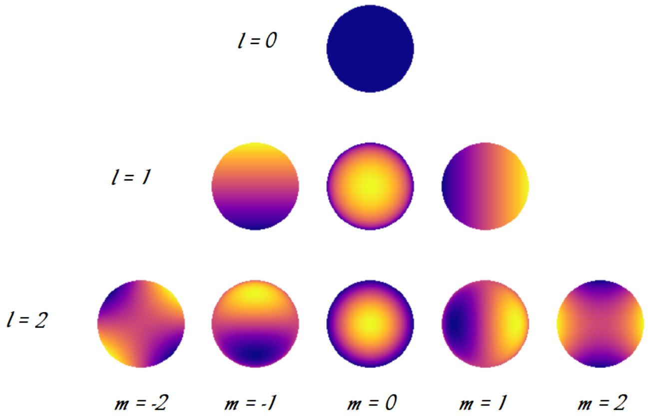


Figure 1.1: The first three order of spherical harmonics. l indicates the order, m the index. Source: [Luger, 2018]

1.2 Related work

The goal of illuminating an environment in a post-process instead of actively setting up lights has received much interest in the past from the vision and graphics community but none focused on building a portable device to support the simulation of arbitrary emission patterns.

For omnidirectional light sources, an algorithm exists, which served as the inspiration for our work. In this case, a lamp is used to sweep the environment, while recording a video. The captured imagery can then be used to relight the scene [Salamon et al., 2017].

Multiple projects study the interaction of light and objects by projecting light from a fixed measurement setup around the object [Debevec et al., 2000; Hawkins et al., 2001; Levoy et al., 2000; Tunwattanapong et al., 2013]. A big disadvantage is that most of these projects require large constructions that are hard to bring to different locations and cannot be used to project outwards into an entire room.

Until now only a couple of projects exist that direct light patterns outward into an entire room. Most of these projects are about screens to be looked at. These screens can take the form of a sphere, or a spinning ring of LEDs that creates an image through persistence of vision (POV) [GreatScott!, 2017; Groenendijk, 2018; Yamada et al., 2017]. While it might seem possible to use such screens as a light source and emit patterns into the room, their light is diffuse and thus does not allow us to derive a clear projection of the displayed pattern to the surroundings.

1.3 Problem definition and challenges beyond previous work

For this project, the aim is to make a portable setup that projects spherical harmonics outward, making it possible to cover an entire room as opposed to just objects. This project differs from the ones in Section 1.2. Firstly, we need an outward projection instead of an inward projection. Secondly, a certain resolution is required in order to be able to project spherical harmonics, even at varying distances, since not every wall has the same distance to the measurement light bulb.

1.4 Criteria for the prototype

The main criterion for the prototype is that it needs to be able to project spherical harmonics at such an intensity and resolution that the impact of the illumination can be captured by a camera. The photos of these projections can then be used to accurately simulate any light source. This process should be easy and relatively fast, allowing the user to intuitively use this device to simulate lighting options for the room. Another criterion is that the device should be safe to use, portable and cheap, allowing research groups to build one and easily test it out themselves.

1.5 Project dynamics

The project proposer is the Computer Graphics and Visualization (CGV) group, thus the prototype is to be delivered to them. The bachelor graduation project is executed in a group of six people, that is divided into three subgroups of two people. Each subgroup is responsible for a specific part of the project and hands in a corresponding thesis. The distribution of the subgroups is as follows:

- Rob Damsteegt & Jippe van Dunné → control, communication and PCB design
- Sebastian Jordan & Ids van der Werf → power distribution, motors and construction
- Bob van Nifterik & Jurgen Wervers → light sources, the corresponding drivers and camera synchronisation

All of these three theses will cover the project globally and their own subsystems in more depth. The thesis outline given in the next section is therefore specific to this thesis.

1.6 Thesis outline

This thesis contains the general description, design and results of the SH light bulb prototype. The thesis will go into more detail regarding the light source and camera synchronization.

Chapter 2

Requirements for the system

In this chapter, an overview of the requirements of the system is given.

In general, the product should be able to project SHs at a certain light intensity so that the reflections of the pattern can be captured by a camera. The required camera settings are strongly dependent on the type of room, e.g. the amount and direction of lighting in the room. Therefore, the assumptions on the environment in which we aim the product to be working will be specified first. After that, the requirements for the system in order for it to work in the assumed environment will be stated.

2.1 Assumptions on the system and its environment

To be able to simulate lamps, all different light colours need to be simulated. However, we assume that a proof of concept of this device can also be given if the measurement light bulb only projects in one colour. This will not allow for every lamp to be simulated, since only monochromous simulations are possible.

We also assume that the lamp can be tested in a dark environment, in case the lamp is not bright enough to create visible projections in a lit up room. This allows for a proof of concept even if the light source is not powerful enough for projections in daylight.

2.2 System requirements

In Section 1.4, some system criteria for the prototype were specified. In this section, these criteria will be further specified and quantified. First some definitions will be elaborated, followed by the requirements.

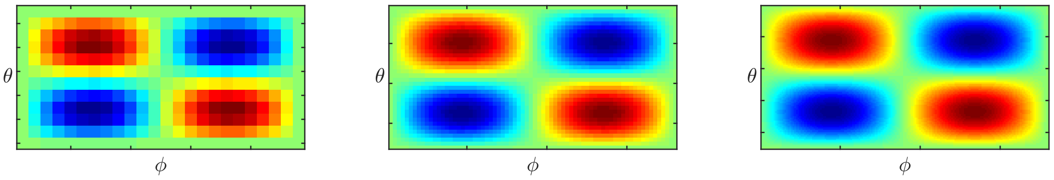
Some definitions that are important for understanding the requirements are given below.

Pattern: This is the projection of one spherical harmonic (SH), of which one or multiple photos can be taken.
Measurement: This is a complete set of patterns, which together form a complete picture. For example, one pattern could be an SH of any of the orders that are desired to display. If the first three orders of SHs are displayed, this means 9 (=1+3+5) SHs in one measurement. Since all the SHs require a positive and negative projection (except for order 0), this results in 17 photographs.

The requirements for the system are listed below and in Table 2.1, where they are specified in three categories: must have, should have and could have.

Angular resolution

The angular resolution of the projection is defined in degrees. This resolution is the same for both the longitudinal as the latitudinal direction. These values were chosen based on simulations. 15° allows for the SHs to be distinguished, but for an accurate representation, an angular resolution of at least 5° is required. A plot for indication can be seen in Figure 2.1.



(a) Angular resolution of 15° (b) Angular resolution of 5° (c) Angular resolution of 2°

Figure 2.1: Three plots of the spherical harmonic function of order 2, index -1 at different angular resolutions

Projection time This is the amount of time one pattern projection takes. It is proportional to the resolution and inversely proportional to the speed of the motors. It is required that it takes a finite time to project the pattern correctly, but ideally, this is in the order of a minute or a second.

Power Since portability is a criterion, the choice of the power source is important. The most simple source of power is a regular power outlet, but for more portability, an implementation with a battery would be more suitable.

Start-up time This is the time required between switching on the device and the start of the first pattern projection. This involves spinning up the motors, buffering the projection from the memory and synchronising the system. Between pattern projections, the time required for setup is less, because the motors are kept spinning and only the memory needs to be updated for the next pattern.

Dimensions For better portability, smaller dimensions are preferable. The prototype should fit through a door, so measurements of any room can be taken.

Phase drift Phase drift is the deviation in average speed of the projection over one of the two axes. Ideally this average speed deviation would be zero, because then the pattern does not shift over the sphere. The allowable amount of phase drift is the same for both axes. The values for this are chosen based on the angular resolution, meaning that they are the same amount of degrees per revolution (divided by two, to account for the positive and negative direction of the phase drift).

Maximum phase error This is the maximum phase error of the projection caused by vibrations or instabilities of the system. This means that there can still be a phase error while the phase drift is zero. The maximum phase error is the same for both axes and has the same bounds as the phase drift.

Colour of the light source To simulate any lamp, the projection should contain all colours. However, monochromous design can also suffice for a prototype.

SH orders The more SH orders are projected, the more accurate the resulting computer simulations can be. It is required that at least the SHs up to order two can be projected for simple simulations.

Brightness This involves the power of the light source on the device. The power should at least be high enough to be able to capture projections in a dark room. However, higher power would allow for capturing in brighter environments, ideally in daylight.

Light levels The amount of different light levels contributes to the resolution of the projection. The more light levels, the less quantisation noise occurs in the projection. However, since the camera has 14 bit light levels, a higher accuracy than this is not visible.

Camera synchronisation For capturing these projections, synchronisation with the camera is desired. This allows the exposure time to contain exactly one pattern projection, which minimises the amount of captured noise light.

User interface For controlling the device, a user interface (UI) is required. Any working UI suffices for the prototype but a graphical UI (GUI) is preferred for a more intuitive experience.

Table 2.1: Overview of complete system requirements

Type	Must have	Should have	Could have
Angular resolution	15°	5°	<5°
Projection time	”converges”	$1\,\mathrm{min\,pattern}^{-1}$	$1\,\mathrm{s\,pattern}^{-1}$
Power	230 V, 16 A	-	battery powered
Start-up time	<15 min	<1 min	<10 s
Dimensions	1 m x 1 m x 1 m	”fits through door” <0.8 m for smallest rib	0.4 m x 0.4 m x 0.4 m
Phase drift	$7.5\,°\,\mathrm{rev}^{-1}$	$2.5\,°\,\mathrm{rev}^{-1}$	$<2.5\,°\,\mathrm{rev}^{-1}$
Maximum phase error	15°	5°	<5°
Colour of the light source	monochrome	-	RGBW
SH order	0-1-2	-	higher orders
Brightness	Capturable in completely dark room	-	Visible in daylight
Light levels	8 (3 bit)	256 (8 bit)	16384 (14 bit)
Camera synchronisation	Change settings and take pictures manually	Change settings manually, use microcontroller to take pictures	Everything done by microcontroller
User interface	working UI	-	GUI

Price A requirement that does not have a must/should/could have value is price. However, the goal is to make this prototype relatively cheap, since that makes it accessible to research groups to reproduce and use for themselves.

Safety Safety constraints should also be taken into consideration. Some parts of the light bulb may be moving, which the construction should support. Also, the light bulb needs power. The system that takes power from the mains should be safe and intuitive to use in order to avoid electric shocks or a short circuit. A safety system should be included in the design, so that in case of any failure or danger, the system shuts down by itself.

Chapter 3

Design overview

At first, some different design options were drafted. Of these options, one was chosen. An overview of these design options and the reasoning behind the choice can be read in Appendix F.

In this chapter, an overview of the final design will be given. First a general overview is given, followed by a short breakdown of all the subsystems and their placement on the construction.

3.1 Design

A basic overview of the design is given in Figure 3.1. It consists of a laser which is aimed at a fast spinning mirror, driven by a motor (marked 'M'). This construction is driven by a motor (marked 'B'), which rotates slower, such that a small angular step is taken for each complete rotation of Motor M. This allows the laser beam to turn over two axes and to project onto a sphere around itself, as depicted in Figure 3.2. In this figure the colatitude is indicated by θ and the longitude is indicated by ϕ.

In this process, the laser 'draws' the spherical harmonics on the walls of the room it is positioned in. Since spherical harmonics contain positive as well as negative values, but 'negative light' does not exist, the positive and negative parts are projected with separate patterns. This can later be compensated for in post-processing.

These projections are captured by a camera, of which the exposure time is controlled to capture an entire projection, so that every part of the room is lit once.

This system is controlled by a microcontroller, which regulates the rotation speeds for both axes, controls the laser and handles communication with the user. This controller, together with some other subsystems, is placed on a printed circuit board (PCB), which is mounted on the moving construction. Power is fed to the system through the lower axle using a slip ring. Control signals for Motor B and the camera are also sent over this slip ring.

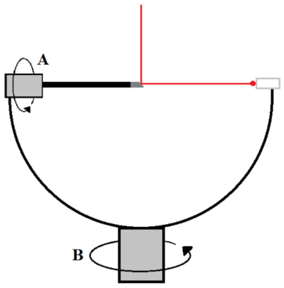


Figure 3.1: Impression of the measurement light bulb design

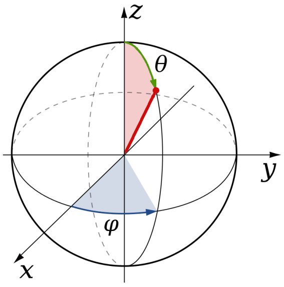


Figure 3.2: Depiction of red laser beam moving over two axes. Source: [Ibrahim, 2009]

3.2 System breakdown

The system consists of seven subsystems which are discussed in this section. The location of the subsystems in the final design can be seen in Figure 3.3.

Controller The controller is the one that binds all the subsystems together. It monitors speeds and angles, reads pattern data and converts it to a drive signal for the laser and controls the motors.

Motor M(irror) This motor rotates the mirror. Motor M is implemented with a DC motor and a driver to operate it. The motor as well as its driver are placed upon the moving construction. Attached to the axle of this motor is the mirror. The driver has a pulse-width modulation (PWM) signal as input, which dictates the speed. The speed of this motor is monitored by a Hall effect switch, which gives a pulse on each rotation.

Motor B(ase) This motor is used to rotate the upper part of the construction. Motor B is implemented with a stepper motor and a driver to operate it. Motor B and its driver are located in the base of the construction and control signals are transmitted from the controller through the slip ring. This slip ring is placed upon the lower axle and the stepper motor is moved off axis and connected with a belt. The stepper motor driver has two inputs, a direction input which determines in which direction it spins and a step input, which makes the motor rotate a step for each pulse sent to it. The speed and orientation of this motor are monitored by a Hall effect switch.

Laser The laser and its driver are also placed upon the moving part. The laser is focused on the mirror using a lens. The laser driver takes a PWM signal as input and produces an accurate drive signal for the laser.

Bluetooth module The Bluetooth module is for connecting the device to for example a phone, which allows the user to control it from a distance. It also enables transmission of pattern data from the user device to the lamp.

Camera The camera is connected to the controller via the slip ring. It is synchronised with the complete system using the microcontroller to make be able to capture exactly one projection with as little noise as possible.

Power supply The power supply is partly on-board and off-board. The on-board power supply contains some voltage regulators, which produce the voltages required for all the different subsystems. This on-board power supply takes a 12 V DC input supplied from the off-board part.

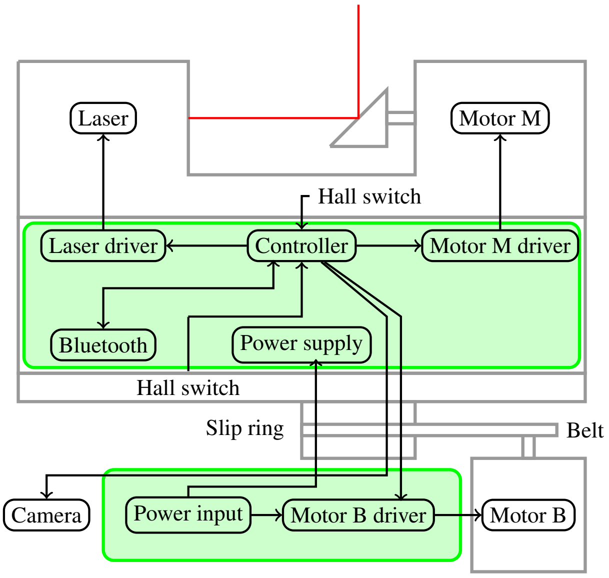


Figure 3.3: Design overview. Circuit boards are depicted by a green frame.

Chapter 4

The Light source

In this chapter, the light source that is employed in the final prototype will be discussed. The properties of different light sources are discussed and compared with similar types of light sources.

4.1 Requirements

The requirements of the light source follow from the Requirements of the whole system as described in Table 2.1.

Resolution The Resolution is stated to have a 15°opening angle in Table 2.1 as must have. A smaller opening angle is more convenient in most cases because a smaller amount of light power is needed. When having a smaller opening angle the simulations will take longer as a result of more rotations needed. The resolution is dependent on the whole system, due to the moving inaccuracy of the light source. Therefore the minimum resolution equals the accuracy of the light movement. The minimum resolution is set at 0.9°.
Power and regulations The light will project a pattern that needs to be detected. Therefore the requirement for light intensity is that it needs to be bright enough to fully detect a pattern and reflections. The power the source emits needs to be within the safety regulations of the TU Delft.
Colour The simplest implementation to make the principal of the SH projections work is by using just one wavelength. A wider spectrum would be preferred, since different objects reflect different wavelengths in different ways.
Light levels The source needs to to have at least 3bits of intensity levels. This is the minimum number of light levels needed to be able to project the first three orders of spherical harmonics. The upper limit is 14 bits. Higher than 14 bits does not change the detected pattern due to the fact that the camera has 14 bits of intensity levels.
Dimensions and weight The light source will be spinning so there are some dimension and weight limitations. The source must be able to fit in the final construction and be as light as possible.
Laser beam profiles The laser beam profile or shape of the laser projection, is of importance for the software to know how to project the patterns. With an asymmetric profile the projections become extremely difficult. Therefore a light source is needed with a circularly symmetric profile, preferably Gaussian.

4.2 Optical properties

The light source chosen in the final design of the SH lamp is a laser. Still, the most commonly used small efficient light sources are LEDs(light emitting diodes). There are some differences and advantages of using a laser over an LED in this device.
LED and laser differ in quite some ways. The size of the diodes itself is almost the same. But there is a great advantage when using a laser. This is the fact that the light needs to be focused with some kind of lens. This lens is a fragile component and needs to be placed very accurately. The lens needs to be

able to focus the light in a 4°divergence angle. For LED light sources in particular, commercial lenses and especially lens cases are rarely available. This is a different case when looking into laser lenses. There is a great market for laser lenses and corresponding housings, of all kinds of purposes. This makes laser lenses a cheap and more reliable solution compared to LED lenses. Another option would be to make a custom lens case but then the dimensions, weight and reliability will, in most cases, be lower that the prefabricated ones.

By definition a light source is monochromatic if the emitted light consists of only one wavelength. According to this definition neither LEDs nor lasers are monochromatic, but lasers closely approach monochromaticy since their spectral distribution resembles a narrow peak on a specific wavelength. LEDs on the other hand can not be considered monochromatic since their spectral distribution is in the shape of a normal distribution spread over a range of about 100 nm, depending on the LED. The power spectral density of a laser is shown in Figure 4.1. Lasers can also be combined to create an RGB appearance [Hollemann et al., 2000]. A laser of this type covers 90% of the light visible to the human eye this is done by combining three lasers of different wavelengths so this RGB laser does not have a spectral power distribution like a regular LED, but it has three peaks on the specific wavelengths of the three used lasers. This RGB laser has a great disadvantage since the spectrum consists of three peaks the light will appear a certain colour to the human eye but will behave different when reflected upon objects. This is a problem since the goal is to gather information regarding the reflection properties of ”complete spectrum” light. LEDs on the other hand can be combined to create an RGB source with such a ”complete” spectrum [Rensselaer Polytechnic Institute, 2003]. There is an advantage in the almost monochrome spectrum of the laser. When using low power, which will be the case for the prototype, the filtering of background light is a convenient way to work around excessive background light. A filter normally works with a certain part of the spectrum that is able to pass through. When working with almost monochrome light, everything besides these wavelengths can be filtered out. This will result in much less light that will interfere with the signal and therefore a lower powered source can be used for the same result. As seen in Figure 4.1 a LED has a lot wider spectrum than a laser. Therefore, when working at low power, a laser is more desirable, because of the fact that the background noise can be partially reduced by a filter.

4.3 Safety regulations

Lasers are available in a wide variety of power ratings, they go up into the orders of watts, however high powered lasers can be hazardous to the eyes and skin. In extreme cases it can even affect the users of the device, as well as bystanders. Therefore lasers are classified in safety levels as shown in Figure A.1. Each laser class has its own regulations, increasing the strictness of these regulations when the rated power of these lasers increases. To work without any LSOs(laser safety officers) and in specialized labs, a rating of 5 mW is the maximum allowed laser rating by the TU Delft university regulations, which falls into class 3R.

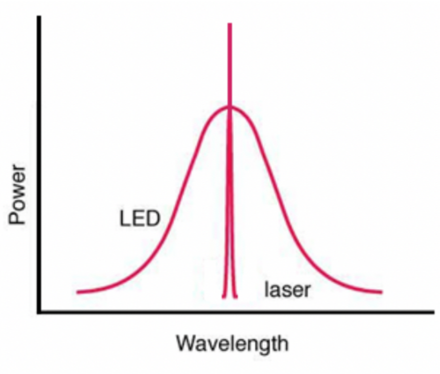


Figure 4.1: PSD of LED and laser

4.4 Laser testing

The first testing of the laser should give an indication if the laser, with power output rating 5mW, would fit the requirements. Especially the distribution and intensity requirements because these are hardly documented in data sheets. To drive the laser, a laser driver is needed, which behaves like a current source. For a more in-depth design of the laser driver see Chapter 5.

The unknown parameter of the laser is the light distribution of the light output. To project the spherical harmonics accurately the light distribution needs to be known and therefore be measured.

4.4.1 Laser beam profile

A lot of lasers, especially cheap ones, rarely have a perfect Gaussian distribution. The distribution is then a so called a quasi Gaussian distribution [Laserglow Technologies]. The light shapes in this case more like an oval. The level of this deformation is with each type of diode different.

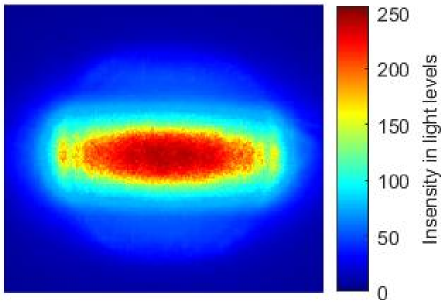
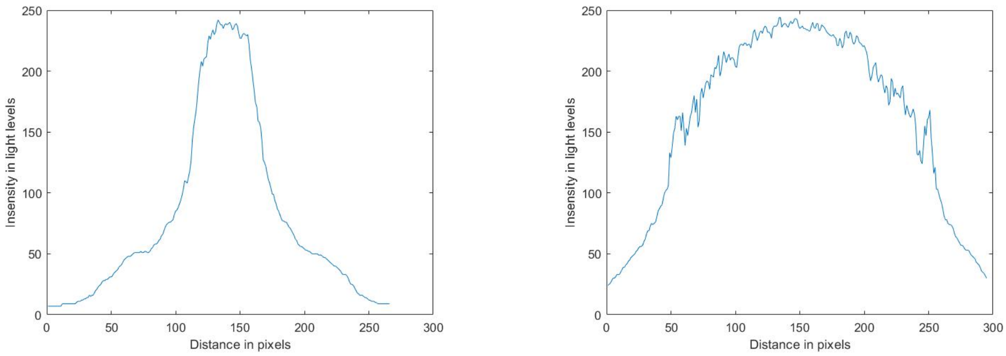


Figure 4.2: Measured profile of the 5mW laser.



(a) Laser distribution cross section vertical

(b) Laser distribution cross section horizontal

Figure 4.3

The measured result of a 5mW cheap laser diode, which is used in the final prototype, is shown in Figure 4.2. The measurement is done by a camera and contains some noise. The distribution is clearly oval and not a dot profile. Figure 4.3a and Figure 4.3b show the cross section of the measured profile relatively to Figure 4.3a, vertical and horizontal. When looking at the sections of the profile a quasi Gaussian distribution can be seen. The laser beam profile is not a dot and not fully Gaussian distributed. Even within the same type of laser diodes the distribution differs. A test report of this phenomenon can be found in Appendix E. Overall, it makes it hard to implement in the measurement light bulb. More powerful and more expensive single mode laser diodes have a more Gaussian and dotted profile. A single mode laser diode emits only one TEM(transverse electromagnetic mode) as opposed to multi mode diode which emits multiple TEMs. Multi mode diodes are usually used to achieve higher powers. As a fully Gaussian dot profile beam, a so called a TEM_{00} beam, is commercially available [Laserglow Technologies]. The subscript represents the radial and angular mode orders [B. F. Hochheimer, J. T. Massey, 1964]. The laser used in the prototype is a single mode near TEM_{00} laser resulting in the quasi Gaussian profile. The assumption is made that in any further model a Gaussian laser will be used. This is because of the complexity of the calculations for calculation the spherical harmonics when using non-circularly symmetric profile.

4.5 Conclusion light source

The light source of the SH lamp will be a laser. This has some advantages compared to other light sources. Mainly the size, cost and availability. The use of a laser comes with the limitation of the TU delft laser regulations. This has as result that the power of the laser is set at a maximum of 5mW. The beam profile of the laser used is not perfect Gaussian but quasi Gaussian. Even between the same type of laser their is a deviation in beam profile, this makes it unreliable. This will not be taken into account any further. This is because of the increasing difficulty when calculating with these unreliable quasi Gaussian profiles. Therefore the choice was made to assume a perfect Gaussian distribution during further calculations.

Chapter 5

Laser driver design

In this chapter the complete design of the laser driver will be discussed, as well as the design process which led to the final prototype.

5.1 Introduction

To drive the laser a driver circuit is needed. The laser needs to be driven safely, which means sufficient protection is present for both the users of the devices as well as for the fragile components like the laser diode itself. The laser diodes are very fragile components and can break due to sudden small deviations in voltage or even static electricity. Therefore a driver circuit was designed and built for the final prototype of the measurement light bulb.

5.2 Requirements

The driver circuit has certain requirements which are not found in Table 2.1, but are still needed for proper functioning of the light source and thereby the complete system.

Output power The required light output power of the laser diode is 5mW, this can be achieved by letting the operating current of the diode flow trough the laser diode. This operating current is between 25mA and 35mA[Laser Components], differing per diode. While the threshold current of the diode is between 18mA and 24mA[Laser Components]. Therefore it is required that the current through the diode is at least 24mA to ensure that the laser is able to turn on. The current should not exceed 35mA since this will result in a light output power of more than 5mW and therefore violate the safety regulations of the TU Delft. With regards to the safety regulations it is preferred to operate in the lower end of the 24 to 35mA range to ensure that the light output power does not exceed the allowed 5mW.
Frequency response The PWM input frequency of the laser driver circuit is 328 kHz, therefore the must have bandwidth is 328kHz to ensure minimum functionality of the circuit. The should have of the circuit is bandwidth of 3.28Mhz. Since a square wave has a lot of higher harmonics as can be derived from Fourier series this is the minimum to have a decent transmission of a square wave trough the driver circuit. A could have for the bandwidth is 32.8Mhz. This way up to the 100^{th} harmonic could be transmitted and therefore the PWM signal could be transmitted almost completely since the power spectral density in the orders above 100 is very low. This will be discussed more in depth in Section 5.3.2
Rise time Because of the fact that the input is a high frequency PWM signal the slewrate of the driver circuit is important, if the slewrate is too low, errors will occur. The rise time should be as small as possible but to ensure the functionality of the laser driver, the rise time should be lower than 10% of the period of the PWM signal.
Overshoot Since the PWM signal is a square wave which consists out of a lot of higher order harmonics, it is very likely some overshoot will occur at the output of the drive circuit since some of the lower harmonics

might be transmitted better compared to the higher harmonics. Next to that, since parasitic capacitances are constantly charging and discharging due to the PWM signal, oscillations can occur. The must have for the overshoot is an overshoot such that the peak stays below the maxiumum current rating of 35mA. When the driver drives the laser with a current of 25mA, the overshoot must be lower than 40%. For overall reliability the overshoot should be as low as possible.

5.3 Design process and choices

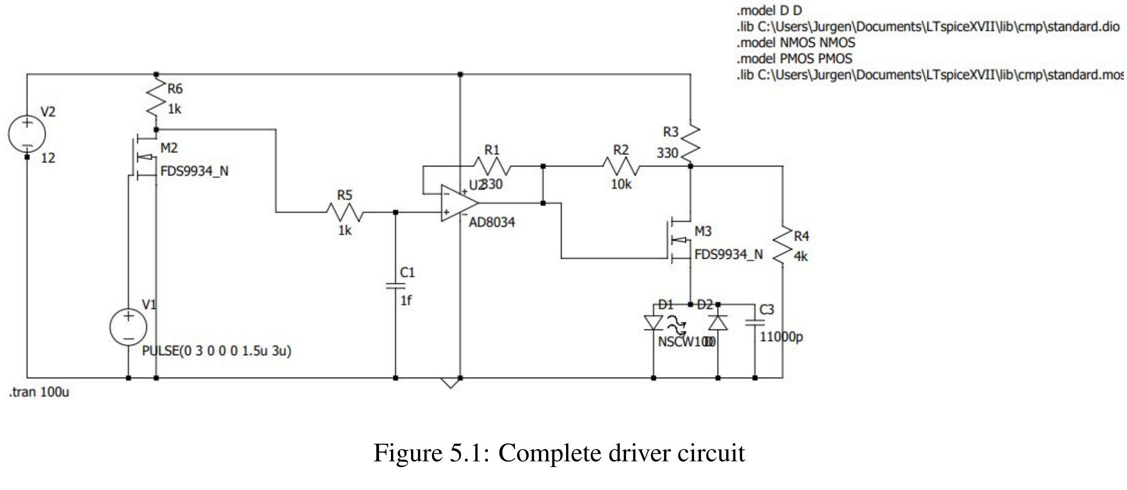
5.3.1 Base design

First of all the type of driver is chosen, since the output power of the laser diode is in a relatively wide region almost linear to the current flowing through the diode, a current-source based driver was chosen. This is preferable over a voltage source-based driver since the laser diode has a certain cut-off voltage after which the diode behaves almost like a short circuit. This causes the current and therefore the output power of the diode to undergo very large changes for small changes in output voltage. This causes the output power to be unstable and furthermore the safety features cannot be guaranteed when using a voltage source-based driver design.

The base of the current source is an N-channel MOSFET which is switched on and off by an opamp. The base principle of the current source is that the laser diode and the MOSFET have a specified and known voltage drop and hence the remaining voltage is found over R3 and the resistance of the MOSFET in Figure 5.1. By Ohm's law the current trough the resistor and transistor and therefore also the current trough the laser diode can be determined.

According to the datasheet the voltage drop over the laser diode in forward active mode is 2.2Volts[Laser Components], however measuring multiple of these diodes revealed that the actual voltage drop is equal to 3.03Volts. The Static DrainSource On Resistance of the MOSFET is equal to 0.025Ω [ON Semiconductor, 2003]. The rated current of the laser diode is 25mA[Laser Components] and the Drain-Source diode forward voltage of the transistor is equal to 0.73Volt[ON Semiconductor, 2003]. Using these values the value for R3 can be determined. Since the source voltage of the driver is equal to 12Volt the following equation can be made when the diode is in forward active mode: $I_{diode} = \frac{V_{source} - V_{diode} - V_{transistor}}{R_3 + R_{transistor}}$ This can be solved for R3 and hence rewritten as: $R_3 = \frac{V_{source} - V_{diode} - V_{transistor}}{Idiode} - R_{transistor}$ Filling in the values results in a value of 329.6Ω. The nearest often used and widely available value is 330Ω which was therefore chosen.

Next to that the resistor R4 is placed for biasing purposes by allowing leakage currents to flow away. R1 and R2 are placed for loop stability and overall stability of the opamp.



```
.model D D
.lib C:\Users\Jurgen\Documents\LTspiceXVII\lib\cmp\standard.dio
.model NMOS NMOS
.model PMOS PMOS
.lib C:\Users\Jurgen\Documents\LTspiceXVII\lib\cmp\standard.mos
.tran 100u
```

Figure 5.1: Complete driver circuit

5.3.2 Frequency characteristics

After choosing for a design based on a current source the right frequency characteristics had to be realized. since the input signal is a pulse width modulation(PWM) signal it is essentially a sum of different sines by the Fourier series of a square wave. So for a frequency of 328kHz a bandwidth of at least 10 times that frequency is needed to have a decent transmission of the PWM signal. For complete transmission of the square wave a bandwidth of around 100 times the frequency of the PWM signal is required. Therefore an opamp with a large bandwidth was chosen. The chosen opamp is the AD8033 this opamp has a gain-bandwidth product of 80 Mhz[Analog Devices, 2008]. Since a pre-amplifier is used as discussed in Section 5.3.3 the gain of the operational amplifier is one. This results in an available bandwidth of 80MHz. Another advantage of using this opamp is the fact that this opamp can be operated by a single supply. Using a single supply opamp eliminates the need for a virtual ground and therefore simplifies the circuit. A low-pass filter is implemented at the input of the opamp to filter out noise components. This filter has to have high enough cut-off frequency such that it does not interfere with the higher harmonics of the PWM signal. The filter was implemented with a simple RC filter. The value of of the capacitor C1 in Figure 5.1 is only a placeholder, no actual capacitor has to be placed in the final design since the parasitic capacitance between the opamp and the ground is around 2pF[Analog Devices, 2008]. This will result in a cutoff frequency of $\frac{1}{2\pi\cdot RC} = \frac{1}{2\pi\cdot 1000\cdot 2\cdot 10^{-112}} = 79.6\mathrm{MHz}$ When using a 1000Ω resistor. The value for this cutoff frequency is placed on the boundary of the bandwidth of the opamp in order to ensure that the opamp operates solely within it's bandwidth. Another frequency characteristic which has to be accounted for is the rise time of the PWM signal and therefore the slew rate of the opamp. The maximum rise time of the signal at the output should be one tenth of the PWM period and is therefore equal to: $\frac{1}{10} \cdot \frac{1}{328000} = 3.049 \cdot 10^{-7}$. The voltage difference is 12Volts, therefore the required slew rate is equal to: $\frac{12}{3.049\cdot 10^{-7}} = 39.36\frac{\mathrm{V}}{\mu\mathrm{s}}$. The slew rate of the AD8033 opamp is equal to $80\frac{\mathrm{V}}{\mu\mathrm{s}}$[Analog Devices, 2008] and hence the opamp satisfies the required rise time.

5.3.3 Pre-amplifier

Because of the limited gain-bandwidth product available with opamps, a pre-amplifier is implemented in the design. The amplifier is based on a N-channel MOSFET, the same as used in the base circuit of the current source, the reason that the MOSFET used in this amplifier is identical is due to the fact that the FDS9926A is a convenient package containing two of the same MOSFETs. The topology of the amplifier is a common source amplifier. The common source topology is a widely used topology for voltage amplifiers. An option might be to directly drive the current switching MOSFET using the output of the pre-amplifier, but this could result in an unstable system since this eliminates the feedback that is present in the opamp circuit. Next to this the output impedance of the opamp circuit is a lot lower than the output of the MOSFET circuit.

5.3.4 Implementation safety features

At last the safety features for the laser diode have to be implemented. First a diode in opposite polarity to the laser diode is placed. In case that bias currents were present. in reverse polarity direction of the laser diode, these currents can now pass trough the safety diode instead of the laser diode. If these currents would have to pass through the laser diode it is very likely to break. Another benefit of this diode is that if by any mistake the power supply is reversed the current can flow the same way as stated for the bias current and protect the laser diode in that way. Another safety measure taken is the capacitor placed in parallel to the laser diode. This capacitor makes sure the signal over the laser diode is smoother than a regular PWM signal, since the laser can break due to sudden changes in current when using just the PWM signal to drive the laser.

5.4 Simulations

The complete circuit was simulated in LTspice. The MOSFETs and opamp in LTspice are models of the exact components in the final design. The laser diode is a diode which closely resembles the actual laser diode. The model of the laser diode might later be replaced with a custom made model for the actually used laser diode, but more measurements have to be performed before implementing this. The output current of the LTspice simulation can be seen in Figure 5.2.

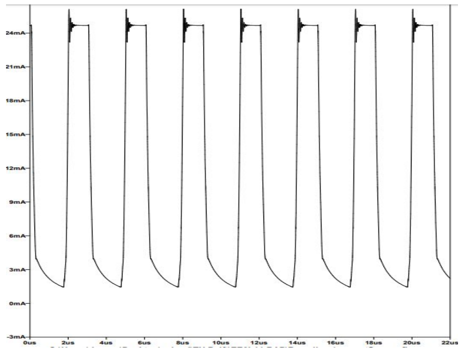


Figure 5.2: simulation of the driver circuit

The output current of the driver circuit is equal to 24.680mA and therefore meets the requirements of the output current. There is an overshoot present was to be expected because of the higher harmonics, the peak of the overshoot is 26.10mA, this results in a overshoot percentage of 5.75%, which also falls within the requirements. The rise time of the current as seen in Figure 5.2 is equal to 0.2μs. This results in a rise time of 6.56% of the period of the PWM signal and therefore falls within requirements. Further it can be noticed that the current does not go to zero when the driver should be turned off, this is most likely because the capacitor is still discharging during that time. Since Lasers, unlike LEDs will not operate below a threshold current[Ott, 1997]. This will not pose a problem since the threshold current of the laser diode is equal to 18mA[Laser Components].

5.5 Results and discussion

The output current of the driver was measured with a multimeter to be 29.61 mA. The actual waveform of the output current is hard to check since oscilloscopes only measure voltage. One way to work around this is by measuring the voltage drop over a shunt resistor. A shunt resistor is a very small resistor. However, since the final circuit was built on a PCB, it was not possible to add a shunt resistor for measurement purposes. The measurement which was performed is a linearity test which maps the input PWM signal to an output light intensity. This test is documented in Appendix D. By reviewing these tests it can be concluded that the light intensity perceived by the camera is not completely linear with the PWM signal received from the controller.

Chapter 6

Camera synchronization

6.1 Theoretical light intensity

This section contains the theoretical analysis of the propagation of light power with respect to the power of ambient light. Several models will be discussed and different reference light settings will be compared. Resulting in a model that estimates the power of the laser propagating in space in different ambient light settings. Also reflection light intensities will be modeled.

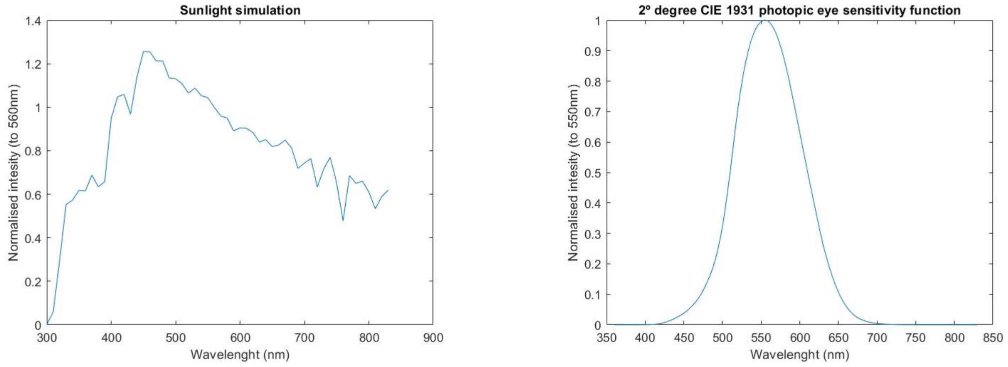
6.1.1 Light as noise

In the most ideal case the SH light bulb can be used in clear daylight in every possible room. This is not realistic because there is a limited amount of light power that can be used regarding the safety regulations. Staying within the 5mW of a power as light source is the most ideal case concerning these safety regulations, since this eliminates the need of a laser safety officer. The problem that comes with lower powered light sources is that the ambient light(the light that is in a room and not produced by the light bulb) will interfere with the pattern. There will be a certain threshold from which on it is not possible to observe the light which is generated by the measurement light bulb. This is due to the addition of this ambient light. This problem will become even more pronounced when trying to capture the reflections.
The question is what ”noise” in this case means. The biggest ”noise” component interfering with the pattern will be ambient light. When the ambient light is constant, the emitted pattern is not greatly disturbed by the ambient light. The light imaged pattern can be compared with the normal constant ambient light and the pattern can be retrieved. When the ambient light is not constant, the imaged pattern can not be compared with a normal constant ambient light. This will result in a distorted, or even invisible, pattern.
Not only is the ambient light interfering with the pattern. The camera sensors are not ideal either. This means that the camera will have a certain error when detecting light. This error will result in a detection of false light that looks like ”white noise”. This noise will always be present. But when working with lower light intensities this noise will be relatively more present.

6.1.2 Power of ambient light in different locations

This section will discuss different ambient light levels and compare them with the intensity of the 5mW laser. Several calculations are needed to get to the right units to be able to make an objective comparison.

The ambient light in the room is determined by all the light sources that produce light in the room other than the measurement light bulb. Figure 6.2a shows some general light intensities for different purposes. The intensity is expressed in lux ($lumen/m^2$), where one lumen is one candela per steradian. Expressing the light power in lux is not a convenient way to calculate the differences in light intensity. Lux is a photometric unit. This means that lux takes in account that the human eye is more sensitive for some wavelengths than other wavelengths [MacAdam, 1938]. To get to the radiometric unit, so the value where all wavelengths are treated the same way, the luminosity function is need. In this function the different wavelengths are weighted when converting power to lux. To model the distribution the 2°CIE 1931 photopic eye sensitivity function is used [E. Fred Schubert] and the Matlab package Pspectro [Matlab extention pspectro]. The function is shown in Figure 6.1b.



(a) (b)

Figure 6.1: Sunlight power spectral distribution(left), 2nd degree CIE 1931 photopic eye sensitivity function (right)

To calculate the light intensity in w/m^2 the light power spectral density is needed. Therefore an assumption has to be made. The assumption is that all the additive light in a room can be turned off. This will result in only direct sunlight which will interfere with the signal, the power spectral density of sunlight is known and can be found in Figure 6.1a.

The formula for lumen is given by Equation 6.1 [E. Fred Schubert]:

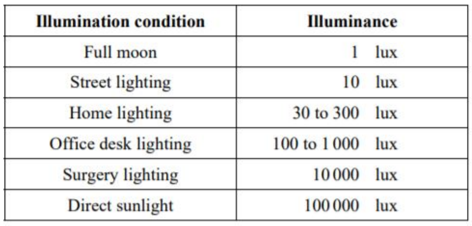
$$\phi_{Lum} = 683 \int_{\lambda} V(\lambda)P(\lambda)d\lambda \tag{6.1}$$

Where $V(\lambda)$ is the luminous efficiency function or eye sensitivity function and $P(\lambda)$ the power spectral density. Using Table 6.2a, and setting this equal to the light intensity, of the reference values, in the different settings, an estimation of the needed light power can be made. First the value from the table, in lux(lumen/m$\hat{2}$), needs to be converted to lumen. Therefore a certain effective surface is needed. The effective surface is the surface witch the laser is illuminating. The size of this surface is determined by the divergence of the laser and the distance form the the projection to the laser. The light source used in the SH light bulb will diverge of 4 °. This means that on 2 meter distance of a wall you have an effective light surface of $\pi * (2 * tan(4°))^2 = 0.061m^2$. Then using the table and setting the room as "street lighting". The total lumen in the effective area of "street lighting" is 0.61 lumen. The second step is to convert the values in lumen to W/m^2.

A laser as light source has a almost monochrome spectrum, this means that only the power of the ambient light with respect to the laser wavelength is of importance with regard to the distortion of the recorded signal. For now the assumption will be done that there is a narrow bandpass filter of 650nm is available. Using the data from [Matlab extention pspectro] of the simulated sunlight spectrum and the reference light power from Figure 6.2a. The light power in lumen, of the 650nm component can be calculated. When looking at Equation 6.1, the function $V(\lambda)$ and the value of ϕ_{Lum} are known. The value $P(650)$ can be calculated using Figure 6.1a and Figure 6.2b .

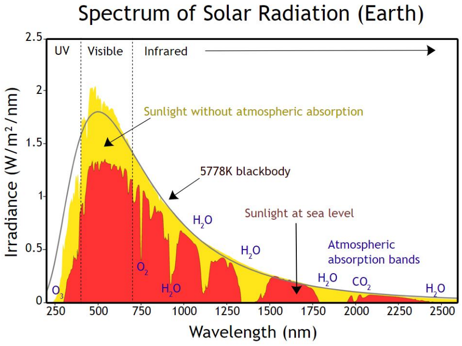
$$\phi_{Lum650} = 683 \int_{0}^{\lambda_{MAX}} V(650)P(650) = Referencevalue(lumen) \tag{6.2}$$

It can be concluded from Equation 6.1, that a change in intensity in lux scales linearly with respect to the power spectral density ($P(650)$). This property is used to convert the Table 6.2a to w/m^2. The reference



Illumination condition	Illuminance
Full moon	1 lux
Street lighting	10 lux
Home lighting	30 to 300 lux
Office desk lighting	100 to 1 000 lux
Surgery lighting	10 000 lux
Direct sunlight	100 000 lux

(a) Table of common light intensity's at different settings [National Optical Astronomy Observatory, 2015]



(b) Spectrum sunlight in $w/m^2/nm$. [Iqbal, 1983]

Figure 6.2: Sunlight power spectral distribution(left), 2nd degree CIE 1931 photopic eye sensitivity function (right)

value of the power spectral density function is taken from Figure 6.1a. Setting 100,000 lux direct sunlight equal to $1.7W/m^2$. The results are shown in plot Figure 6.3. Where the intensity needed is plotted against the distance from the light source to the illuminated plane. The plot shows that the 5mW laser as source can only be used in low light environments. The results shown in the plot only apply to the direct illumination. It does not take reflections into account.

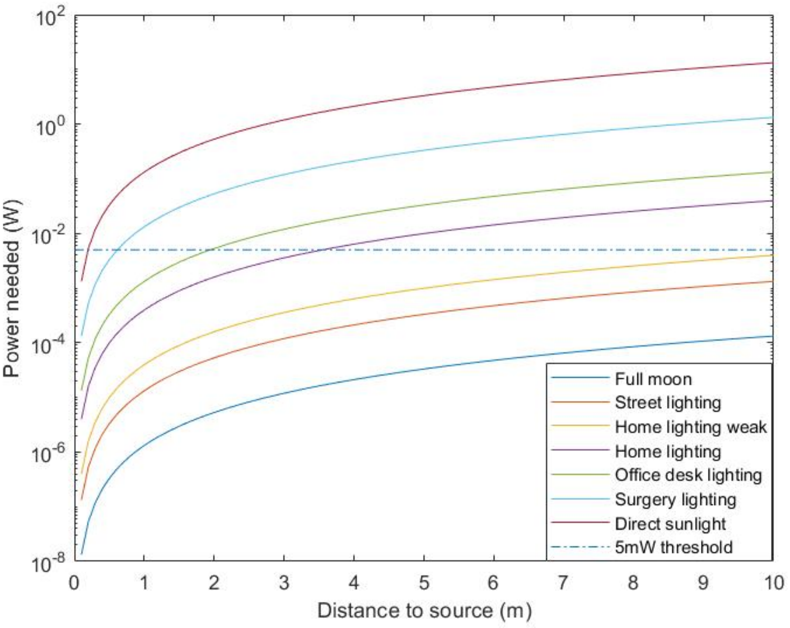


Figure 6.3: Noise power in 650nm wavelength against the distance in different settings

6.1.3 Modeling reflected power

To be able to get results from the SH light bulb not only the power of the direct illumination, but also the reflections should be higher than the noise level. Reflections are hard to model. Aspects like colour, shapes, materials and distances of the space, the lamp is placed, have in have huge impacts in the reflections of the lamp. To prevent going too deep into this topic the objective becomes to see if the principle on itself is possible when being in an almost ideal case.

The most simple model will be the most perfect case. This means that the wall on which the light is projected fully reflects the light specularly. In this case it is just possible to extrapolate on the plot shown in Figure 6.3. This only holds when the light is specularly reflected. When not in this ideal case things become complex quickly. The specular reflections become diffuse reflections when using non ideal materials as illumination object [David J. Eck, 2013]. To model this behaviour an estimation has to be made. That almost all the light gets diffusely reflected, so that the lamp is projecting onto a matte material. Also the estimated reflection efficiency is assumed to be 100%. Consequently the fully diffused light is spread in all directions away from the projection point. Therefore the reflected light energy can be estimated as radial radiation and follows quadratic law of a half sphere. The result is shown in Figure 6.4 and the script used can be found in Appendix B. In the figure two horizontal lines are shown. These lines represent the threshold at which the noise at the reference values, as described in Figure 6.2a for moonlight and streetlight, exceeds the light intensity of the projected signal. From Figure 6.4 it can be seen that when being in a "moonlight" intensity environment, the first order reflections can be detected until 1.4 meter from the wall of the initial projection.

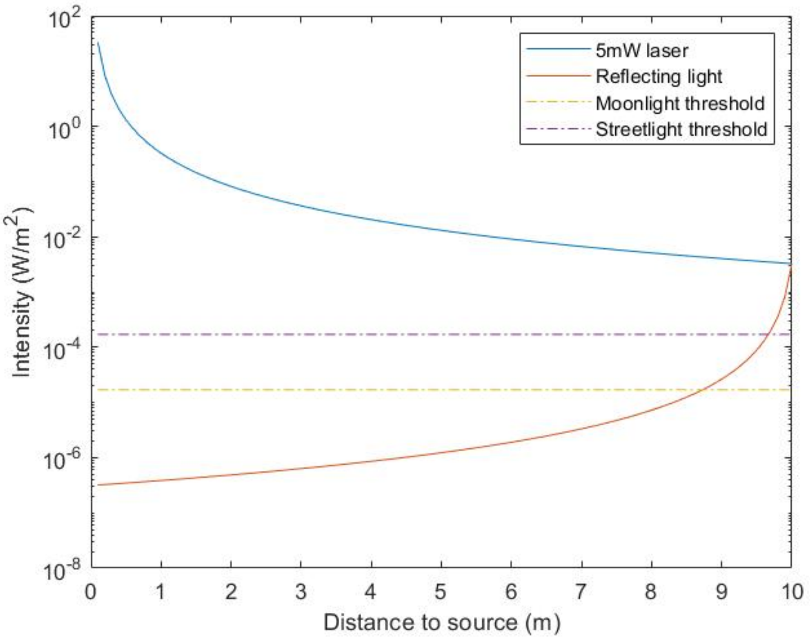


Figure 6.4: The decreasing light intensity true space and reflected signal when projecting at 10 meter distance. The noise intensity's are shown in horizontal lines.

6.1.4 Light detection

The projections and reflections gets digitized with the use of a digital camera. The CMOS sensor in this device works with RGB pixels. There is a matrix of photon sensing cells with a red, blue or green filter. This means that all of the three independent pixels have some spectrum where they are most sensitive. To optimize the signal to noise ratio, ideally a pass band filter of only the light source is used. The green and blue pixels in this case do not mater because they can be filtered out afterwards. The red pixel on the other hand will always see a pixel as red when something within his sensitivity region gets detected. Therefore a physical filter can be used. The simulations above included the assumption that there is a narrow-band pass filter used and only took in to account the noise in this spectrum. When not using a filter or using a less narrow filter there will be more noise interfering with the signal.

Additive light

The detected light is additive, which means that light intensity is a sum of all light observed. Light measured by a camera can therefore be subtracted. When subtracting the zero measurement of the picture. The ambient light in the measurement picture will be removed. Therefore the noise in the picture will be decreased and even light that has less power that the ambient light has a possibility to be retrieved.

6.2 Camera (delay) tests

To ensure accurate camera synchronization, tests to measure the delay when taking pictures were performed. The camera delay tests can be found in Appendix C. From the data gathered from these tests it can be concluded that the delay until a picture is taken is fairly unpredictable.

6.3 Light intensity measurements

The laser is rated at a certain light output power. To see if the power of the laser is enough to make a projection, the camera settings and filters are tested. Eventually, comparing them if they match the predictions of Section 6.1. The goal is to see what camera settings are optimal, and if the light intensity is enough to observe reflections.

6.3.1 Measurement setting

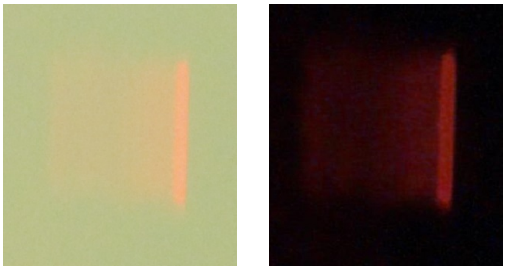
The modeled situation in Section 6.1 is done with reference values. To literally test the laser in light settings like moonlight, is not convenient. Therefore a almost dark room is used. The dark room has some background noise and comes close to a ”moonlight” like environment.

The tests are done by changing the camera settings. Then taking pictures at different situations. Since the camera has 14 bits of intensity levels, and a maximum of intensity it can detect, saturation can become a problem. When saturation occurs the pixels that saturated have the same maximum value. In reality they should defer form each other and be higher than this saturated value. This adjusts the light ratio of the projection. The data detected then becomes useless for the purpose of this project.

The reflections are a lot weaker signal then the first projection. Therefore the first projection is a lot earlier saturated than the observed reflections. When being in a almost dark room the shutter can be opened a long time before the noise is observable on the resulting picture. An equilibrium has to be found in the saturation of the first projection and observably of the reflection. As seen in Figure 6.5 the power of the laser is so low that even using a long shutter time the pixels do not get saturated. This means that the most optimal camera setting is to keep the shutter open right before the first pixels saturate. The exact length of the shutter time depends on the noise level in the room. The ISO, that can be described as the light sensitivity of the sensor. The higher the ISO the more sensitive for light the sensor is. The downside of a high ISO is the amount of noise it adds. Therefore a longer shutter time and lower ISO is preferred over a high ISO. Increasing the ISO on the other hand can help by detecting low intensities.

6.3.2 Physical light filter

To lower noise at the red detection pixel of the camera sensor, a light filter is used. As described in 6.1.3 a physical can reduce a lot of noise. Narrow band light filters are rather expensive. The costs of this will be out of the budged of the prototype. Therefore a cheaper alternative is used. The filter used is a 026 bright red Lee filter, the transmittance spectrum can be found in Figure A.3. These kind of filters are mostly used in the theaters to generate colored light from normal white spotlights. The profile is not a band pass, but a high pass filter. The cut off lays around 620nm. This filters out the part of the spectrum that the red detection pixels are most sensitive for. The spectrum of camera sensitivity can be found in Figure A.2.



(a) Projection with ambient light (b) Background subtracted

Figure 6.5: Moving laser measurement

Revision noise intensity

The filter used for the camera is not near the ideal one as described in Section 6.1.2. The filter was stated to be a delta spike band pass filter with 650nm as only transitions wavelength. The filter used is a high pass filter. This means that a lot more noise will interfere with the red detection pixels of the camera. Combining the spectrum of the filter in Figure A.3, the spectrum of sunlight in Figure 6.1a and the sensitivity of the red pixels of the camera in Figure A.2, there can be an estimation made of how much the noise increases when using this filter. This is done by estimating Figure A.2 linear in the region from 600nm until 700nm with a efficiency scaled to 650nm. The spectrum of the filter is approximated with a delta step function on 620nm. The sunlight distribution was included in the Matlab package Pspectro so this data is already known. This result in a increase in noise of a factor 93.5. The ”moonlight” noise level of 6.1 will therefore shift from $1.7 * 10^{-5}$ to $1.6 * 10^{-4}$ W/m^2.

6.3.3 Image possessing

Even with a high noise level use full data can be extracted. As said before, the light is additive. So when having two pictures, one with the projection and one without, the images can be subtracted. This principal shown in Figure 6.6. This can be used till the light intensity pixels get saturated. There is a downside to this method of noise reduction. The photos have to be at the exact same place and have the same noise distribution. The images get subtracted so any movement of the camera will give a shift in the subtracted image. In Figure 6.6 a clear horizontal line can be seen. This line is the result of a shift due the movement of the camera shutter.

(a) With projection (b) Without projection (c) Subtracted image five times multiplied

Figure 6.6

6.4 Synchronizing the camera

The main goal of synchronizing the camera is to find the right camera settings and synchronizations signals, to lower the noise as much as possible. This to get a clear representation of the projected pattern and reflections. This chapter looks at the options for synchronizing the camera followed by the consequences this synchronizing has on the noise over the system.

In theory, when the level of light of the projection is higher then the noise level, the projection can be recovered. The fact that the light source is moving makes it more difficult to still retrieve data from the pattern with light levels that are close to the noise level. A projection is made up by the principal of integrating the light that moves along its path in space. The camera is therefore also integrating noise over the time the shutter is open. When the laser passes by, the noise that gets added to the signal, is the sum of noise that the camera detects within the shutter time. Therefore for noise reduction, the ideal case would be to take as small steps as possible of light propagation in a picture. This will result in the noise power level as described in Section 6.1. The camera used for imaging the pattern has a predictable delay when taking one picture(see Appendix C). When more pictures are taken sequentially the delay becomes unpredictable. Taking more pictures with a shorter shutter time, therefore becomes almost impossible with the camera used. To prevent the unpredictable delay at long exposure times, at leas 0.5 seconds of waiting time has to be implemented between the taking of two pictures. Because of this delays one picture will be taken every projection to prevent delays form deforming the projection
The slow axes of the lamp will rotate at 0.5 Hertz. This means that a whole projection will take 1 second. When setting the camera at exactly one second exposure time, the location at witch the laser is in the projection does not mater. The image will always contain exactly one projection. As seen in Appendix C taking a picture itself also has a unpredictable factor in its delay. To prevent the delay of having a influence on the image, the camera will start the photo at a place where errors have the least influence on the projection. As shown in Figure 6.4 the light intensity greatly decreases when propagating in space. In Figure A.4 a schematic impression is given of the regions that will have influence on the projection based on. Therefore the most distant location of the projection is chosen to have a possible error. This will result in the least distortion of the imaged projection. Because the lamp projects the pattern in a rotating circle. The camera will start making a picture after the laser passes a quarter of the circle after it has passed the camera. This is the most distant from the frame that is in the photo.
When the measured pattern is too low in intensity, a multiple of the projection time can be chosen to add to the shutter time. This causes the camera to detect more than one pattern. When detecting more light of the pattern the intensity will increase. This only holds when the signal is not largely disturbed by ambient light.

Intensity with chosen synchronizing

The chosen synchronizing is not ideal. As discussed before, with this type of camera as measurement device a lot of unpredictable delays are added. So when using this camera this is the way as described in Section 6.3.1. The impact of noise is increased by the way the camera is synchronized. It takes the sum of the noise the shutter is open against a relative short time the light passer at one point. The angle the laser is focused is 4°. The device moves along two axis, so the time an arbitrary in the room is illuminated, is $\frac{4}{360} * \frac{4}{360} * 1\, second = \frac{1}{8100}\, seconds$. This means that the noise intensity relatively to the pattern becomes 8100 times higher. Then reevaluating the simulations of Section 6.1 and using the revised noise intensity of Section 6.3, a new plot can be made. The plot is shown in Figure 6.7 shows the rather big relative noise increase. This theoretical noise increase is much less disastrous than it seems. This factor 8100 is a relative number. The detection of spreading light over time over the shutter depends on the camera and camera settings. When adjusting the film speed or ISO, the relative light differences are captured at smaller time intervals. This means that integrating noise over time has less effect on the final image. additionally, the estimated noise level ”moonlight” is higher than the test setup. Which is an almost completely dark room.

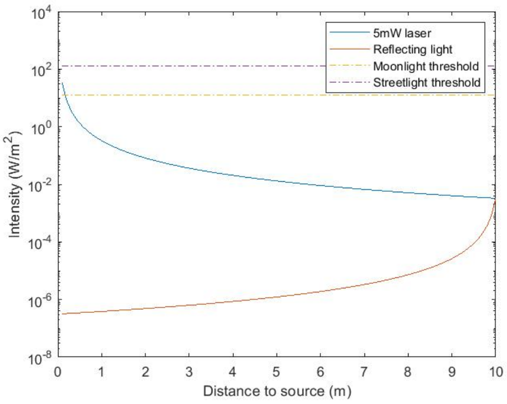


Figure 6.7: Re-evaluated light propagation curves

6.5 Camera synchronization results

The synchronization is tested by making pictures of the moving light source. As can be seen in Figure A.4 there clearly is a pattern present in the captured image. In this case the pattern is a striped sphere. The picture is taken with a higher shutter time than the initial 1 second. This is the case because at the moment of testing the prototype was rotating at 25% of its speed. Therefore the projection takes 4 seconds. To capture the whole pattern a shutter time of 4 seconds is needed. This has as advantage that the camera has less trouble with detecting the pattern. Also a rather high ISO is used. This increases the sensitivity for light, but increases the noise.

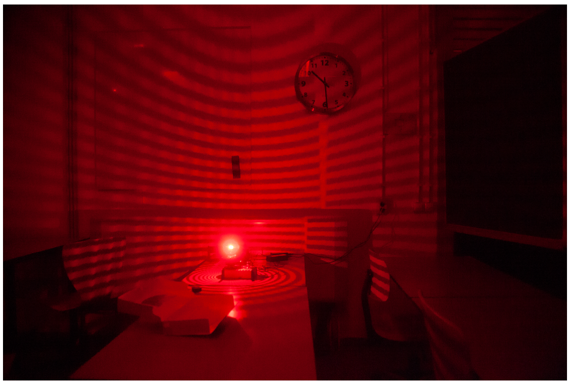


Figure 6.8: Test result with a synchronized shutter time

6.6 Conclusion camera synchronization

With the 5mW laser the camera is able to detect the pattern in an almost dark environment. Any present ambient light will greatly interfere with the signal. Reflections particular are hard to detect when dealing with ambient light. For capturing a pattern a shutter time of at least one whole projection time is needed. After that it scales with multiples of the projection time.

Chapter 7

Prototype implementation and validation results

This section will discuss the last steps in the building of the measurement light bulb. First, the fabrication of the prototype will be discussed, followed by the test results of the complete system.

7.1 Fabrication of the prototype

The final prototype consists of all subsystems as shown in Figure 3.3. The subsystems, separately designed by the subgroups, are assembled together to form the prototype.

The laser, implemented in the final prototype, has an opening angle of 4° and is focused such that the focal point coincides with the mirror. By using this angular resolution, the spherical harmonic can be projected accurately while still limiting the time needed for each measurement. The construction has two axes over which it can rotate, which allows the laser to project onto a sphere around itself. The measurement light bulb acts as a point source, due to the fact the focal point coincides with the mirror, from which the spherical harmonic is projected into the room.

Motor M spins at 200 Hz, while Motor B steps at 200 Hz with steps of 0.9°, thus 400 steps for one rotation. This means that during the projection of one pattern, Motor B rotates 180°, which corresponds with 200 steps. Therefore the projection of one pattern takes 1 s. The microcontroller controls the speed of the two motors and synchronises this with the intensity of the laser to create a pattern. The synchronisation with the camera is not yet implemented, so the camera is controlled and set up manually.

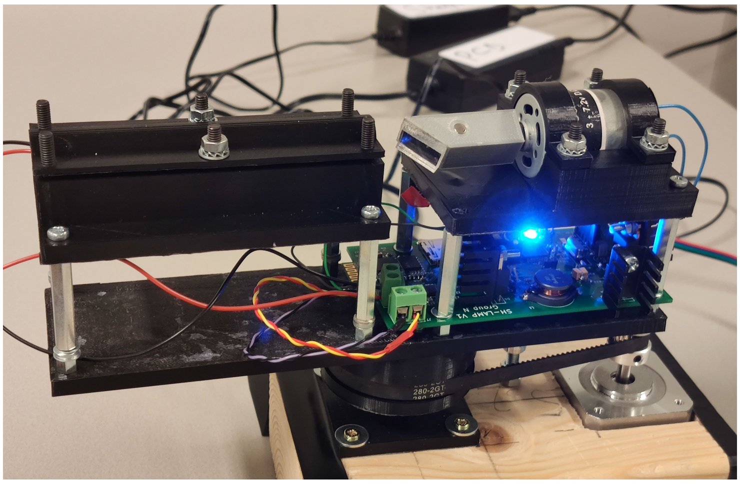


Figure 7.1: A photograph of the prototype

7.2 Results of complete system tests

The goal of this project was to build a measurement light bulb which can project spherical harmonics and to synchronise it with a camera so that the impact of the illumination can be captured. Figure 7.3 shows the result of a projection of the measurement light bulb. The photograph is taken in a dark environment to eliminate as much ambient light as possible, which is required since the laser is relatively low power. The exposure time for this photograph was 8 s. The pattern that is projected is the positive part of the spherical harmonic function of order 2 and index -2, of which a plot is depicted in Figure 7.2.

However, it still contains some errors. The positioning of the Hall effect switch for Motor M causes some offset in latitudinal direction, which should be corrected for. Also, a bug in the projection algorithm causes the spherical harmonic to be projected in two different orientations: once normally, and once rotated 180° over the longitudinal axis. These two errors combined make it that the projection is actually two projections of the same spherical harmonic oriented in slightly different ways.

Also, since the Hall effect switch for Motor B is not yet placed, the measurement light bulb is not yet able to orient itself longitudinally.

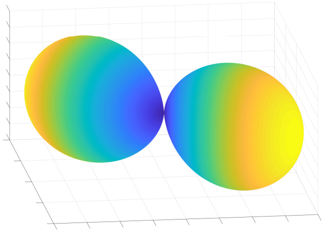


Figure 7.2: Plot of the positive part of the spherical harmonic function of order 2, index -2

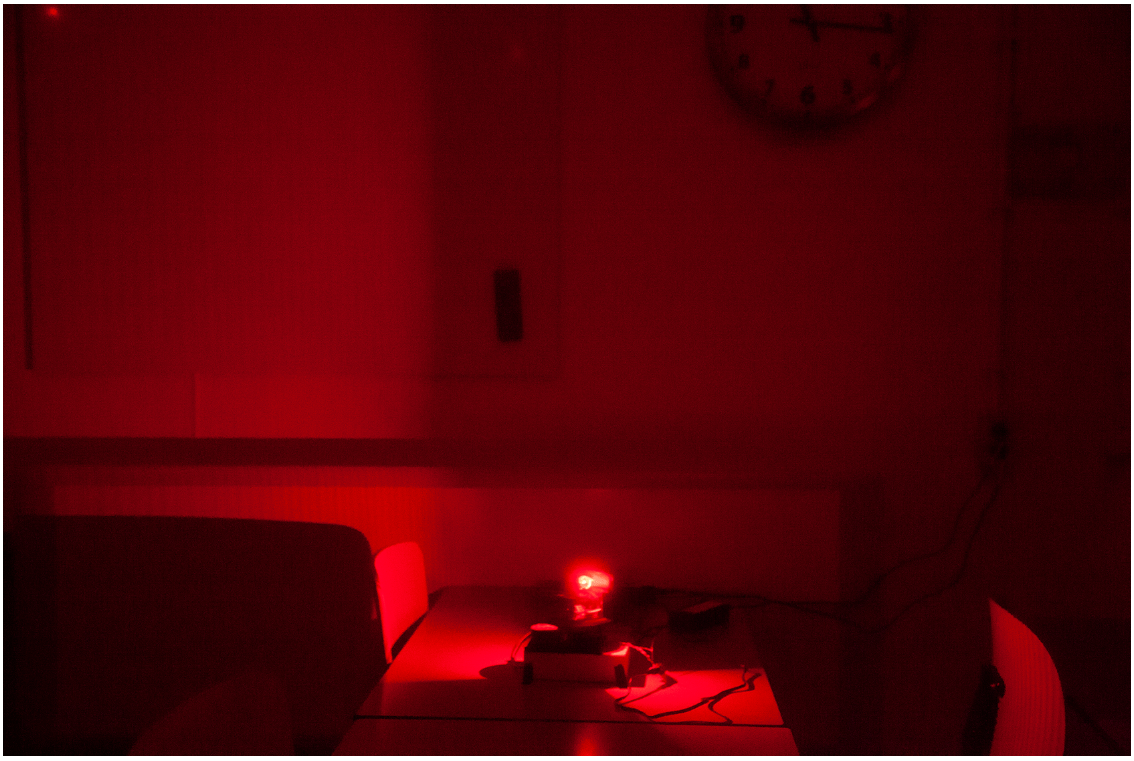


Figure 7.3: A photograph of the first spherical harmonics projection

Chapter 8

Discussion of results

In this section the results of the measurement light bulb are compared with the system requirements, stated in Chapter 2. Table 8.1 shows an overview of the system requirements and the results that are achieved.

Table 8.1: Overview of complete system requirements

Type	Must have	Should have	Could have	Result
Angular resolution	$15°$	$5°$	$<5°$	$4°$
Projection time	”converges”	$1\,\mathrm{min}\,\mathrm{pattern}^{-1}$	$1\,\mathrm{s}\,\mathrm{pattern}^{-1}$	$1\,\mathrm{s}\,\mathrm{pattern}^{-1}$
Power	$230\,\mathrm{V}$, $16\,\mathrm{A}$	-	battery powered	$230\,\mathrm{V}$, $16\,\mathrm{A}$
Start-up time	$<15\,\mathrm{min}$	$<1\,\mathrm{min}$	$<10\,\mathrm{s}$	$1\,\mathrm{min}$
Dimensions	$1\,\mathrm{m}\times1\,\mathrm{m}\times1\,\mathrm{m}$	”fits through door” $<0.8\,\mathrm{m}$ for smallest rib	$0.4\,\mathrm{m}\times0.4\,\mathrm{m}\times0.4\,\mathrm{m}$	$0.24\,\mathrm{m}\times0.24\,\mathrm{m}\times0.20\,\mathrm{m}$
Phase drift	$7.5\,°\,\mathrm{rev}^{-1}$	$2.5\,°\,\mathrm{rev}^{-1}$	$<2.5\,°\,\mathrm{rev}^{-1}$	$0\,°\,\mathrm{rev}^{-1}$
Maximum phase error	$5°$	$5°$	$<5°$	$1.044°$
Colour of the light source	monochrome	-	RGBW	monochrome
SH order	0-1-2	-	higher orders	None
Brightness	Capturable in completely dark room	-	Visible in daylight	Capturable in completely dark room
Light levels	8 $(3\,\mathrm{bit})$	256 $(8\,\mathrm{bit})$	16384 $(14\,\mathrm{bit})$	256 $(8\,\mathrm{bit})$
Camera synchronisation	Change settings and take pictures manually	Change settings manually, use microcontroller to take pictures	Everything done by microcontroller	Change settings and take pictures manually
User interface	working UI	-	GUI	working UI

Angular resolution The final angular resolution of the system is equal to $4°$ and therefore the ’Could have’ requirement is reached.

Projection time Since Motor B has a frequency of $0.5\,\mathrm{Hz}$ and one projection only needs a $180°$ rotation, the projection of one pattern takes $1\,\mathrm{s}$. Thus the and therefore the ’Could have’ requirement is reached.

Power The system is powered using the mains. Therefore the ’Must have’ requirement is reached. In order for the system to be powered by one or multiple batteries, the power supply should be designed differently to be compatible with the battery instead of with the mains.

Start-up time The device can start a measurement within one minute of switching the device on. Therefore the 'Should have' requirement is fulfilled. A faster start-up time would require a faster data transmission when a pattern is uploaded to the device, since this is the bottle neck for the start-up time.

Dimensions The measurement light bulb has the dimensions $0.24\,\mathrm{m}\mathrm{x}0.24\,\mathrm{m}\mathrm{x}0.20\,\mathrm{m}$. Therefore the 'Could have' requirement is reached.

Phase drift The phase drift of the pattern is equal to zero, since the pattern is reset each time Motor M finishes one revolution. Thus, the 'Could have' requirement is reached.

Maximum phase error Motor M is the main cause of the maximum phase error, in colatitudinal direction. The maximum speed deviation of Motor M is $0.29\,\%$, with respect to the steady-state speed. This corresponds to a maximum phase error of $1.044°$ in one revolution. Therefore the 'Could have' requirement on phase error is reached (phase error $< 5°$).

Colour The colour of the projection is red monochrome light with a wavelength of $650\,\mathrm{nm}$. Therefore the 'Must have' requirement is reached. For this project, a monochrome light source is enough to create satisfying results and give a proof of concept.

SH order The software has currently been developed for spherical harmonics of orders 0, 1 and 2. However, due to some bugs in the software, only one of these can be projected. At the moment this is the function of order 2 and index -2.

Also, some unfinished work relating to the Hall switches give rise to some synchronisation issues, which cause double projections at different orientations.

When these are fixed, the device will be able to project all the specified spherical harmonics correctly. When this has been done, the 'must have' requirement can be fulfilled.

Brightness The prototype is able to capture patterns in a completely dark room. Therefore the 'Must have' requirement is reached. To reach the 'Could have' category, the light source should have a higher light intensity than the ambient light. Then, a camera can capture the pattern in daylight.

Light levels The driver and the microcontroller together allow for 256 light levels ($8\,\mathrm{bit}$), thus the 'Should have' requirement is fulfilled.

Camera synchronisation The microcontroller can synchronise the pattern and the camera to take a photograph. The camera settings are set manually by the user. Thus the 'Should have' requirement is reached. In order for the microcontroller to also control the camera settings, an extra (wireless) connection between the microcontroller and the camera is needed.

User interface A user interface has been implemented via a command line interface using a Python program. It allows the user to control the device intuitively using only four different commands. This means that the 'Must have' requirement is reached.

Price The material costs for the measurement light bulb are roughly €150.

Safety The output power of the used laser is within the TU Delft regulations and is therefore considered safe. The prototype can be controlled wirelessly which eliminates the need of being close to the moving parts of the device when performing measurements. Also, a safety measure has been implemented to make sure that the motors and the laser shut down if something gets stuck in them or a part falls of.

Chapter 9

Conclusion and future work

9.1 Conclusion

The goal of this project was to deliver a proof of concept for the measurement light bulb. The final prototype is able to project a spherical harmonic onto its surroundings. However, the prototype only works in a low light environment. In environments with a higher light intensity, the camera is not able to distinguish the ambient light from the the projected light. Patterns can be uploaded to the prototype using a Bluetooth connection. Also, the control signals, like a starting and stopping signal, are managed by Bluetooth. Although not implemented yet, the prototype could support camera synchronisation, to capture the illumination impact of the measurement light bulb.

9.2 Future work

All requirements for the prototype were reached to some extent (Must have/Should have/Could have), yet there are still things to improve on for future versions of the measurement light bulb. This prototype is only used for a proof of concept. A future design for a measurement light bulb could improve on individual subsystems as well as the system as a whole.

Beam profile The current beam profile has a quasi-Gaussian distribution. A future version of the measurement light bulb could contain a laser with a more accurate Gaussian distributed profile or a circularly symmetric beam profile. This will reduce errors in the projections or omit the need for complicated compensation algorithms for this problem.

Light output intensity The current prototype is only able to capture spherical harmonic projections in a completely dark room. A future model could contain a light source with a higher power output. This would enable the measurement light bulb to perform measurements in lit rooms as well as dark rooms. However, this would require the involvement of a laser safety officer.

Spectrum of the light source The current prototype of the measurement light bulb can only emit red light with a wavelength of $650\,\mathrm{nm}$. A future design of the measurement light bulb could improve on this by using a light source that covers the complete visible light spectrum or even a light source that can cover certain parts of the spectrum upon request.

Linearity of light source As seen in tests, the light intensity as captured with the camera is not completely linear with the PWM signal that was fed to the laser driver. A future model of the measurement light bulb could contain a linear laser driver or could compensate for this problem using software.

Camera The Canon EOS 5D Mark II has two main forms of unpredictable delay. Firstly the shutter delay, which is the time between the signal that activates the camera to take a picture and the opening of the shutter. Secondly the buffer delay, which is the time between the end of one exposure and the start of the next, needed for saving the image file. To implement an accurate and efficient camera synchronisation algorithm, a camera with predictable delays is required. In addition, newer camera models often have better image sensors that have better low-light performance, which would give more accurate results.

Light levels Together with the microcontroller, the laser driver is able to output 256 different light levels (8 bit). The sensor of the camera is able to capture 16384 (14 bit) different light levels. Therefore, in a future model of the measurement light bulb, the amount of light levels could be increased up to 16384 (14 bit), equal to the sensitivity of the sensor in the camera.

Construction Although the construction is functional, a few aspects could be improved. Motor B, its corresponding and the power converters can be put into a 3D printed box, which can be mounted to the bottom of the current construction. This way there will be no loose wires or components. This box could also have a mounting point for a camera tripod. This way the system could easily be placed in many position. Another possible point of improvement is the part of the projection that is obstructed by the construction. This obstruction could be reduced if the construction is designed differently.

Start-up time The start-up time of the measurement light bulb is currently around a minute, but this could be reduced significantly if the symbol rate of the Bluetooth communication was increased. Currently, this is set at 9600 Bd, but this could be increased to 115 200 Bd or even to 1 382 400 Bd, for a approximate speed-up of 10 or 100 respectively.

Motor speed To reduce the projection time, the time it takes to capture one pattern, the motors could be driven at higher speeds. In this way more measurements could be performed within a shorter amount of time.

Higher order spherical harmonics Future work could include higher order spherical harmonics to be able to be projected. The hardware of the device is already capable of this, but the patterns for higher order have not been calculated and stored. If this were to be done however, they could be projected.

Power supply The current implementation uses two AC/DC converters. One for the stepper motor and one for the rest of the system. In a future version this could be reduced to one AC/DC, by changing the topology of the power supply. Another improvement could be the use of a battery to power the system. It is expected that a large battery pack would be needed in order to power the whole system.

User interface The user interface could be improved by transforming it into a graphical user interface. This allows for more intuitive usage.

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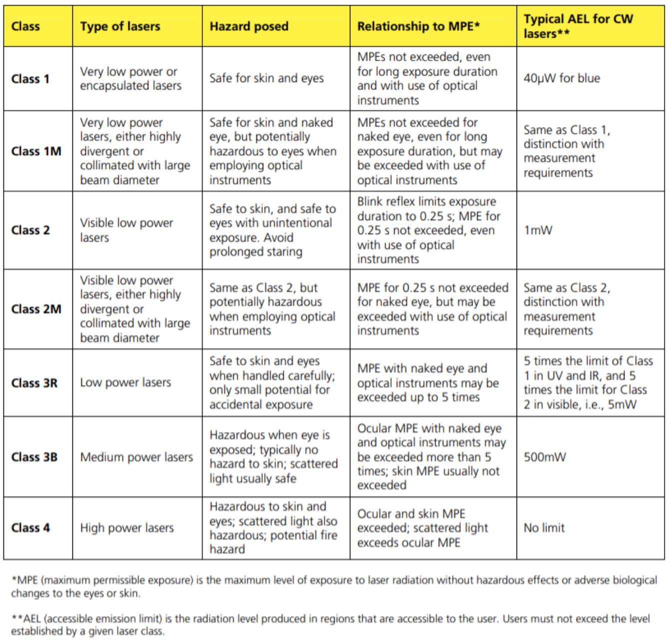
Appendices

Appendix A

Additional figures

A.1 Light source



Class	Type of lasers	Hazard posed	Relationship to MPE*	Typical AEL for CW lasers**
Class 1	Very low power or encapsulated lasers	Safe for skin and eyes	MPEs not exceeded, even for long exposure duration and with use of optical instruments	40μW for blue
Class 1M	Very low power lasers, either highly divergent or collimated with large beam diameter	Safe for skin and naked eye, but potentially hazardous to eyes when employing optical instruments	MPEs not exceeded for naked eye, even for long exposure duration, but may be exceeded with use of optical instruments	Same as Class 1, distinction with measurement requirements
Class 2	Visible low power lasers	Safe to skin, and safe to eyes with unintentional exposure. Avoid prolonged staring	Blink reflex limits exposure duration to 0.25 s; MPE for 0.25 s not exceeded, even with use of optical instruments	1mW
Class 2M	Visible low power lasers, either highly divergent or collimated with large beam diameter	Same as Class 2, but potentially hazardous when employing optical instruments	MPE for 0.25 s not exceeded for naked eye, but may be exceeded with use of optical instruments	Same as Class 2, distinction with measurement requirements
Class 3R	Low power lasers	Safe to skin and eyes when handled carefully; only small potential for accidental exposure	MPE with naked eye and optical instruments may be exceeded up to 5 times	5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 in visible, i.e., 5mW
Class 3B	Medium power lasers	Hazardous when eye is exposed; typically no hazard to skin; scattered light usually safe	Ocular MPE with naked eye and optical instruments may be exceeded more than 5 times; skin MPE usually not exceeded	500mW
Class 4	High power lasers	Hazardous to skin and eyes; scattered light also hazardous; potential fire hazard	Ocular and skin MPE exceeded; scattered light exceeds ocular MPE	No limit

*MPE (maximum permissible exposure) is the maximum level of exposure to laser radiation without hazardous effects or adverse biological changes to the eyes or skin.

**AEL (accessible emission limit) is the radiation level produced in regions that are accessible to the user. Users must not exceed the level established by a given laser class.

Figure A.1: Table of laser classes. Source: [Macquari University].

A.2 Camera synchronization

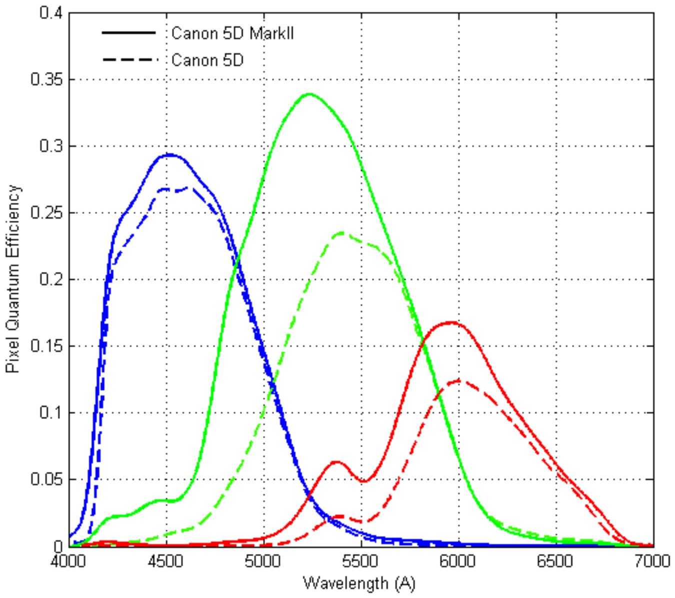


Figure A.2: The camera sensor sensitivity of different wavelengths

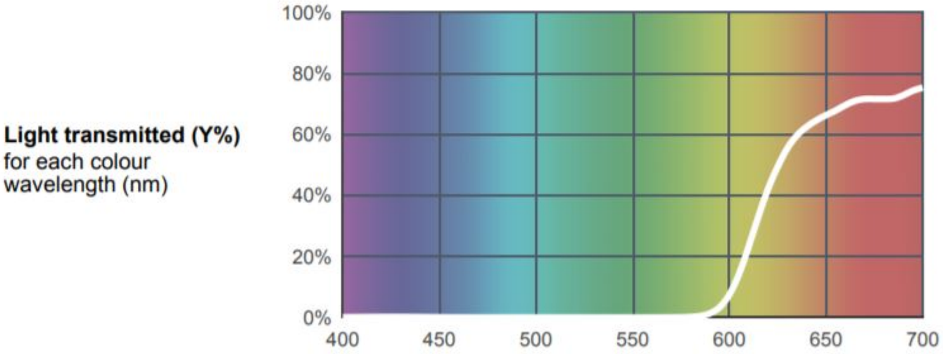


Figure A.3: Light transmittance of the 026 bright red LEE filter

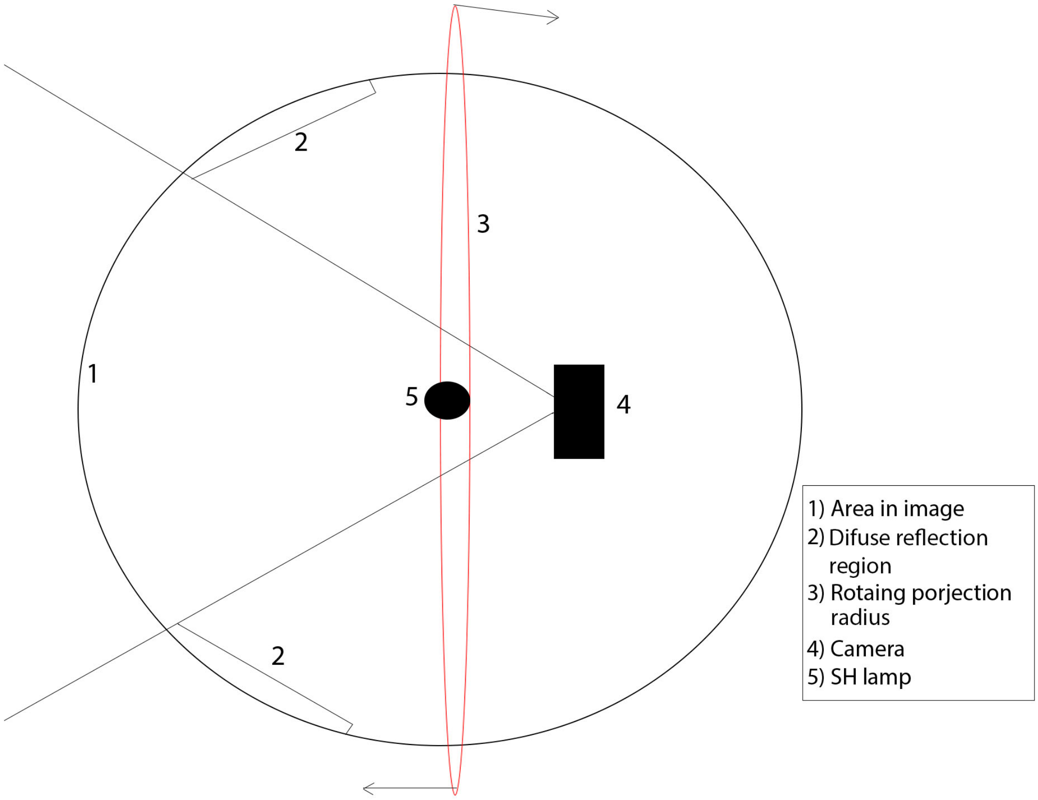


Figure A.4: Schematic representation of the regions used in synchronizing

Appendix B

Matlab scripts

```
PSD650 = 1.7;   %reference value PSD
refsunlight = 100000;  %reference value to sunlight
Illumi = [1,10,30,300,1000,10000,100000]; %inensity in lux
names = ["Full moon", "Street lighting ","Home lighting weak", "Home lighting ","Office desk lighting","Surgery lighting ", "Direct sunlight ", "5mW threshold" ];
distance = [0:0.1:10];
deg = 4; % openings angle

for a = 1:7 % loop true different lines
    power = (PSD650*Illumi(a)/refsunlight)*pi*(2*tand((deg/2)).*distance).^2; %calculate
    semilogy(distance,power);

    hold on;
end
mwatts = distance.*0 + 5*10^-3; % 5 milli wats refference line
plot(distance,mwatts,"-.");
legend(names);
xlabel("Distance to source (m)");
ylabel("Power needed (W)")
```

Listing B.1: Matlab script used to calculate the light power

```
PSD650 = 1.7;  %reference value PSD
refsunlight = 100000; %reference value to sunlight
Illumi = [1,10,30]; %inensity in lux
names = ["5mW laser", "Reflecting light ","Moonlight threshold","Streetlight threshold"];
dist = 10;
deg = 0.5;
distance = [dist/101:(dist/101):dist];

    % calculation of the power propagation of (R) reflecting and (I) initial
    powerI = (5*10^-3)./(pi*(2*tand((deg/2)).*distance).^2); %pi*r^2
    powerR = (2*pi.*(distance(1)).^2)*(powerI(101))./(2*pi.*(distance).^2); %(power * smallest surface sphere/ surface sphere)
    powerR = fliplr(powerR);
    semilogy(distance,powerI);
    hold on;
    semilogy(distance,powerR)

```

```
Fullmoon = distance.*0 + PSD650*Illumi(1)/refsunlight;
plot(distance,Fullmoon, "-.");
streetlight = distance.*0 + PSD650*Illumi(2)/refsunlight;
plot(distance,streetlight , "-.");

legend(names);
xlabel("Distance to source (m)");
ylabel("Intensity (W/m^2)")
```

Listing B.2: Matlab script used to calculate the reflection intensity

```
%srcipts used for moddeling working of the filter
% only look at spectrum of 600nm to 700nm
lightFilter = [0.1:0.1:10]*0;% create empty vector
for i=1:80
    lightFilter(i+20) = 1; %set filter values
end
load sunlight600700.mat; % load sunlight dist;
sun =sun(:,2)/sun(11,2); % scale distribution to 650nm
cameraDist =  linspace(3,0,100); %sensitivaty form 600 -> 700 nm scaled to 650
filtertot = cameraDist.*lightFilter; % make a general filter array by multiplieng two filters
noiseadd = 0;
for i=1:20 % looping true vlaues and summing the addtional noise scaled to 650 nm. Instead of interpolating the vlaues of the sunlight psd the steps size is adjusted.
    sample= i*5;
    add = filtertot(sample)*sun(i);
    noiseadd =noiseadd + add*5;
end
```

Listing B.3: Matlab script used to model the filter to estimate a noise increase with respect the model in Section 6.1

```
%this script is use to analyse the intensity of red pixels in a photo.
clear all
%file names
str = ['010.cr2' ; '020.cr2'; '030.cr2';'040.cr2';'050.cr2';'060.cr2';'070.cr2';'080.cr2';'090.cr2';'100.cr2';'110.cr2';'120.cr2';'130.cr2';'140.cr2';'150.cr2';'160.cr2';'170.cr2';'180.cr2';'190.cr2';'200.cr2';'210.cr2';'220.cr2';'230.cr2';'240.cr2';'250.cr2'];
J = imread('0.cr2'); % zero measurement
for i = 1:25
    I = imread(str(i,:));
    isub = imsubtract(I,J); % substract background
     Ir = isub(:,:,1); % only take red
     Ig =  Ir([((2/6)*3744):1:((4/6)*3744)],[((2/6)*5616):1:((4/6)*5616)]); %"cutting" out part of the image most ideal for measurement
    countvar(i) = sum(sum(Ig));% sum all intensity levels of the pixels
end
x = [10:10:250];
plot(x,countvar)
title('Light intensity scaling');
ylabel('Sum of red pixel values');
xlabel('Lenght of PWM');
```

Listing B.4: Matlab script used to to analyse the intensity of red pixels in a photo.

```
%script used for analising the light beam proffile of a laser, using photos
```

```
I = imread('dab1.jpg');
angle = 60;
J = I;%imrotate(I,angle);
imgA = rgb2gray((J./2)); % make one dimensional
figure
imshow(imgA,jet(256)); % plot intesity in colour levels
colorbar();
a= round(0.5*(length(imgA(1,:)))); %find middle of matrix (horisontal)
vecVera = imgA(:,a);
h = colorbar;
ylabel(h, 'Insensity␣in␣light␣levels')

figure
plot(vecVera);
xlabel("Distance in pixels")
ylabel("Insensity in light levels")
figure
b= round(0.5*(length(imgA(:,1)))); %find middle of matrix (vertical)
vecVerb = imgA(b,:);
plot(vecVerb);
ylabel("Insensity in light levels")
xlabel("Distance in pixels")
```

Listing B.5: Matlab script used for analyzing the light beam profile of a laser using photos

Appendix C

Test: Camera Delay

This test is designed to determine the delay between pressing the remote shutter release and the camera taking the actual picture. For this, the camera is pointed at a display which counts with a millisecond accuracy from the moment the remote shutter release is pressed and after the picture is taken, the time can be read from the picture. The delay measured is specified in Figure C.1.

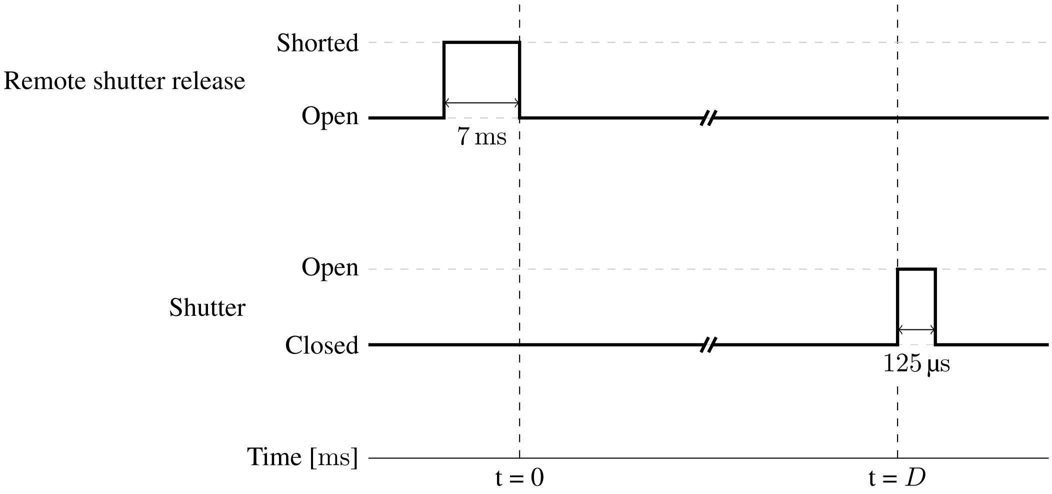


Figure C.1: Time diagram of camera delay test where D is to be determined (not to scale)

To be able to come to conclusions about this delay, 62 pictures have been taken. The delays have been put in a histogram which can be seen in Figure C.2.

We can conclude from this data that the delay is approximately 100 ms.

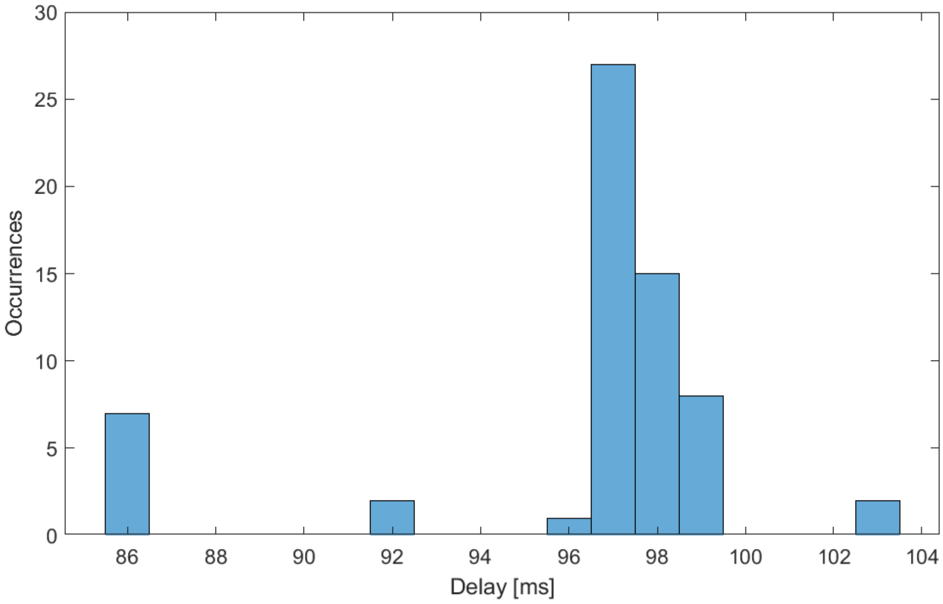


Figure C.2: Histogram of the measured values of D

Appendix D

Test: Light linearity

This chapter contains the testing of the light levels of the light source. The laser driver circuit gives a PWM current driven signal as input for the lasser. The test is based on how the light source will convert this PWM signal into light light levels.

D.1 PWM light level principal

The PWM signal is can be created with different duty cycles. These different duty cycles reassemble the different light levels the light source is able to emit. The most ideal case would be if the light the laser emits is linear to the duty cycle. This means that the laser will linearly transforms the input power into light.

D.2 Measurement setup and method

The measurement will be done by taking the Sh light bulb and projecting a line. The line will be projected in different light levels. This line will be captured by a camera. The camera takes a photo of the projection and reflections. After a picture is made the photo is analyzed using Matlab.
To measure the light intensity of the different projected lines the images are loaded in Matlab, Th script can be found in Appendix B. The most characterizing part of the image is chosen to look at the difference in intensity. This part is cropped and all red pixel values are added. This will give a overview of how many and how intense the light in the picture is.

D.3 Result

The result is shown in Figure D.1

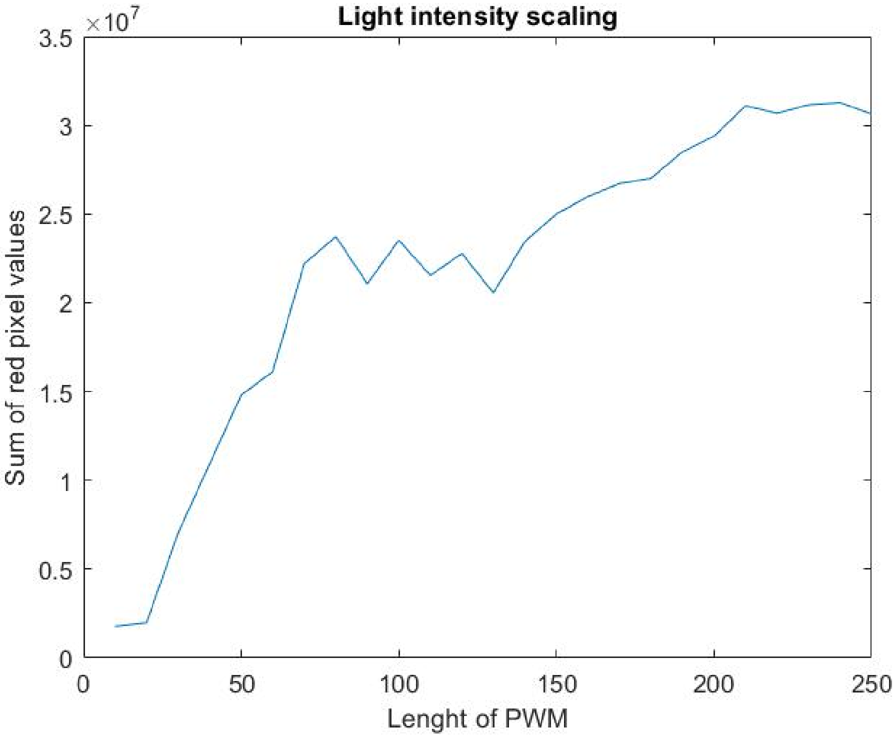


Figure D.1: The different duty cycles against the produces light intensity

Appendix E

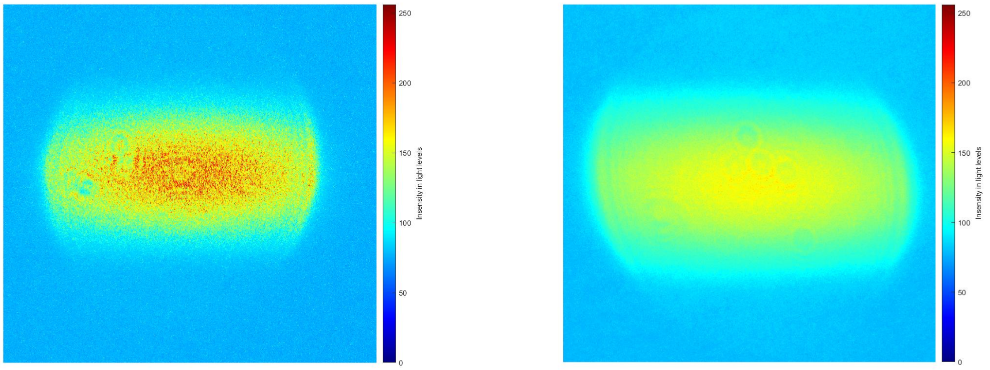
Test: Laser profile

This chapter contains the testing of the laser beam profile. Two different lasers are compared. The comparison will show how much the laser beam profile defers between lasers of the same manufacturer.

E.1 Measurement setup and method

Two laser diode are tested. The laser diodes are measured by making a photo of the projection of the laser beam. This happens with strictly the same camera settings. The environment of the two measurements is taken as constant as possible. Therefore the ambient light will have the same influence on both measurements. The light in the picture than gets averages. This is done in Matlab by converting the picture to a gray scale, see Appendix B for script. This will average the intensity's in a one dimensional matrix. The result is shown in Figure E.1. The vertical section of the captured distribution is show in Figure E.2.

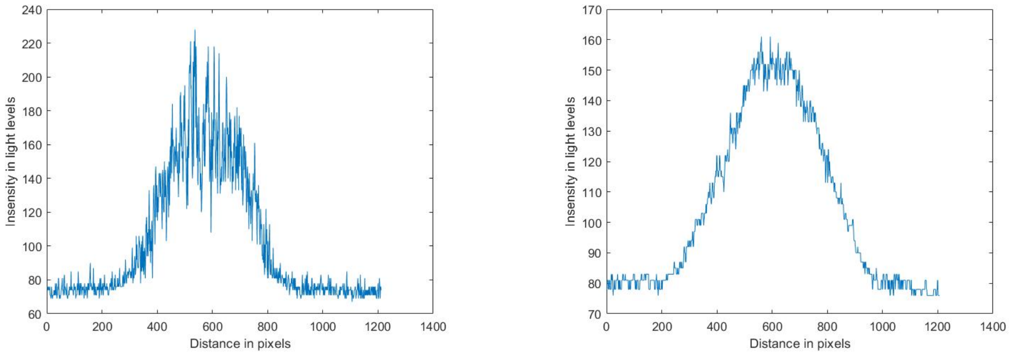
E.2 Results



(a)

(b)

Figure E.1: The two laser profiles



(a) (b)

Figure E.2: Horizontal section of the two laser profile distributions

E.3 Conclusion

From Figure E.1 and Figure E.2 can be concluded that there is a difference in laser beam profile. The plots show a clear deviation in intensity and power distribution.

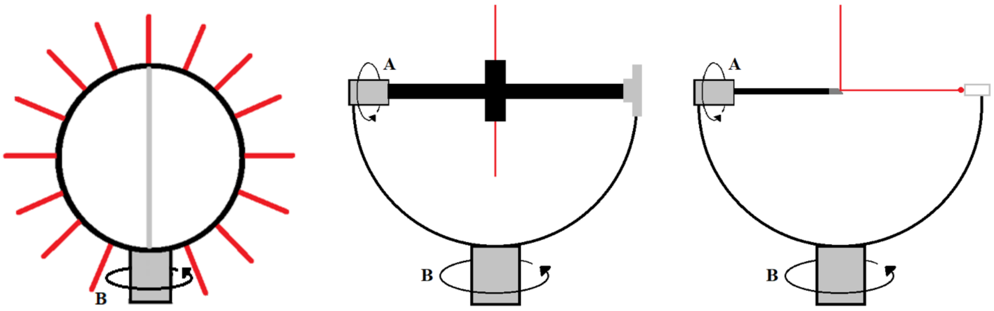
Appendix F

Design choice

In this chapter, several design options will be discussed, the option that was chosen in the end and finally what is to be delivered to achieve this design.

F.1 Design options

At the start of the project, the CGV group proposed a basic idea for an implementation of the measurement light bulb. In addition to this, two alternative implementations were thought of. These three basic implementations could be all solutions to the problem. They all work with one or multiple light sources that spin around to project onto a sphere. The reflections of this light in the room are captured with a camera with a sustained shutter time to capture one or more entire rotations. A brief explanation of the three design ideas is given below, of which the corresponding design impressions can be seen in Figure F.1.



(a) Design 1 (b) Design 2 (c) Design 3

Figure F.1: Sketches of basic design options. Red lines indicate lasers, grey rectangles indicate motors, the letters M and B describe the axes of rotation and the black arrows indicate the direction of this rotation.

Design 1 This design consist of a ring with light sources, which can all be controlled individually at high speed. The ring is rotated around axis B. Due to the rotating movement, the ring projects onto a sphere. By varying the light intensity of the individual light sources during the rotation, the system is able to show light patterns on the sphere.

Design 2 This design consists of one or two light sources that rotate(s) around two perpendicular axes. With the rotation around axis M, the light source(s) will project onto a circle. When this part is rotated around axis B, which is perpendicular to axis M, the device will be able to project onto an entire sphere. By varying the intensity of the light source while the device spins around both axes, it is possible to project different light patterns into a room.

Design 3 This design consists of a rotating mirror instead of a rotating light source. The design uses only one light source that is focused on a mirror that rotates around axis M. In this way the rotating mirror spans up a circle. When this part is rotated around axis B, which is perpendicular to axis M, the device will be able to project onto a sphere. By varying the intensity of the light source while the device spins around both axes, it will be possible to project different light patterns into a room.

F.2 Design choice

After simulating and testing parts of the designs that are mentioned above the third design was chosen as the best.

Design 1 is not a good option because of a trade-off between weight and resolution. Adding more light sources increases the resolution, but increases the weight, which makes the device heavier to rotate. For a resolution that meets the requirements, this would require a lot of lights, which would be infeasible.

For design 2, axis M was built. Unfortunately it turned out to be very difficult to align the axle of the motor, as it needs to be fixed to the construction on either side. Due to this alignment problem, the laser, which is mounted on axis M, was not able to move smoothly and could not reach the frequency stability that is desired for projecting a stable pattern.

For design 3, a test version of axis M was built, of which the test results were promising. It has the advantage that the only part which is spinning at a high frequency is the mirror, which is relatively light, whereas the laser is only moving slowly. This makes it easier to stabilise the system.

These results and the difficulties with the other two designs, lead to the decision to implement design three.