TECHNICAL UNIVERSITY DELFT

MASTER THESIS

BIOMEDICAL ENGINEERING

Lightfield adaptable surgical luminary

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1 Preface

This thesis is submitted in partial fulfilment of the requirements for a Master of Science Degree in Biomedical Engineering at the faculty of Mechanical, Maritime and Materials Engineering at the Delft University of Technology. The work was done at the MISIT group that is part of the department of Biomechanical Engineering.

This thesis involves the development of a surgical luminaire that is able to modify the shape of the light field to the shape of the wound. The different steps of the design process are discussed and analysed. A partial model was made of the final design which has been subject to tests to compare the mathematical results with real-life data. I would like to express my gratitude to professor Jenny Dankelman and Arjan Knulst for sharing their knowledge and support. During the project it became clear that many different aspects come into play when a system is designed that can modify the shape of a light field. The basic idea of placing LEDs on a bendable surface is very simple and elegant. From this simple idea a system evolved with many different subsystems and variables that all influence the functionality in their own way. Each subsystem on its own is not complex, but the complexity comes from the interdependency between them. It was clear that each subsystem had to be examined individually to see the influence it has on the system. During these analyses, the abilities of the system became visible and I was often impressed with how well the system was able to function. It has not been an easy project for me. Often I found myself trying to solve problems that seemed to work fine the day before. Even though this was sometimes frustrating, I am glad that I continued to complete the assignment. Finally I want to thank my family and especially my girlfriend for their patience and support. Without them it would have been impossible to come to this point.

Contents

2 Introduction

Proper lighting is an essential factor during a surgical procedure. Many different luminaire systems are available on the market that all provide lighting in a generally comparable manner. These current surgical luminary systems often consist of a large central light source, sometimes accompanied by one or two satellite light sources and they are manually moved into position. These systems are able to project light towards the surgical field. The shape of the projected light field is determined by the luminary output of the system, the shape of the illuminated surface and the orientation that the luminaire and the target surface have in relation to each other. One set of parameters that control the properties of the projected light field is determined by the suspension arm system by which the luminary is connected to the ceiling. The range of motion of the suspension system determines under which angles the light is able to be projected and what the distance of the light source can be to the surgical area. Another set of parameters is determined by the light source itself. Typical properties of the light source are; the surface area of the light emitting surface, the shape of that surface, the focus point of the light beam, shape of the beam, spectral bandwidth and many more. These properties of the light source determine the shape and light distribution of projected light field. It is this second set of parameters which focusses on the light itself that will play a big role during this graduation project.

3 Problem definition

Vision is a complex and dynamic sensory function. How well a person can see is largely determined by the lighting conditions that affect the illuminated object. Current surgical lighting systems project a round light field onto the surgical field that has a more or less circular Gaussian distribution. Because wounds are often not round in shape it is thought that a circular Gaussian distribution is in many circumstances not the optimal lighting condition. Visual discomfort might arise from the fact that unnecessary areas inside the operating field are being illuminated. Everybody has experienced the effect of trying to look at a dark region when there is brightly illuminated region in front of it. It is difficult to see until you block the bright region with your hand. This effect is also applicable to the situation in the operating room (2, 3). Even though complete blinding might not occur, the situation is often far from optimal. Surgical drapes have reflective properties of 35%, whereas the reflective properties of the wound area are around 8%. This creates a ratio of 4.3:1 which is larger that the recommended ratio below 3:1. The only solution that the surgeon has to compensate for this, is to manipulate the luminary during surgical procedures to redirect the light away from the high intensity areas.
It is believed that providing a light field that is able to adapt its shape according to wound dimensions might provide a better lighting condition and thereby decreasing visual strain and increasing the performance of the surgeon. The main goal is to design a system that is able to provide greater adaptability of the light field, which is able to use information about the wound shape. This must be done without compromising the quality of the luminary in other important areas. Typical areas where the system should provide improvements compared to current systems are; less light projection on unnecessary areas, better uniformity of the light field in relation to the shape of the wound.

4 Requirements

The following section states the requirements that are applicable to the adaptive surgical luminary design. The requirements need to make sure that the luminaire will function properly inside the surgical environment. Many of the requirements are based on the functional aspects of current surgical luminaries. Even though the system is intended to improve the current systems, it is still important to focus the design on improving the necessary elements. The focus during this project will be on the requirements regarding the ”light field” and the ”light”. Requirements that are related to production and cost are taken into account during the design process but will become more important when the design is in a later stage.

4.1 Light field related requirements

- The smallest possible diameter of the light field should be $<$150mm when projecting a circular shaped light field.The luminary must be placed at a distance of 1 meter.
- The largest possible width of an oval shapes light field should be at least $>$300mm.
- The smallest possible width of an oval shapes light field should be at least $<$100mm.
- When lighting an oval shaped wound with a length of 300mm and a width of 100mm, the area of the light field should be smaller than $0.18m^2$. This area corresponds to an oval light field of 400mm by 150mm.
- The wound border must fall within the border of the light field.
- The error between the projected light field and the desired light field must not be larger than 15% on average.
- The border of the light field should be able to produce shapes with a smallest border radius of at least 50mm.

4.2 Light related requirements

(1)

- The colour of the light must be uniform along the light field and remain in the desired color space.
- The intensity distribution must be 80% accurate compared to a desired shape which follows from the user input and predefined shape models.
- The intensity may not exceed 160 kLux at the brightest spot of the light field.
- The device should be able to illuminate 50% of the inside of the predefined wound shapes at an intensity of 40 kLux.
- The total radiance of the luminary may not exceed 1000 W/m^2 at 1m distance.

- The shadows must not introduce noticeable uncommon distractions.
- The light must not produce noticeable flickering or other instabilities.
- The light should not produce unnecessary glare.
- The surgeon’s head may not produce excessive shadows and pass the tests which are specified in the current standards for surgical luminaries.

4.3 Design related requirements

- The device must be small enough to manoeuvre with relative ease and no longer than 1.5m.
- The total weight of the device should allow it to be suspend by current arm systems.
- The device should not extensively disrupt the laminar airflow.
- The device should be easy to clean.
- The device should not contaminate the patient with dust or other particles.
- The system should not be highly complex
- There must be a manual control function
- Operating the luminary should be intuitive.
- The light should remain functionally operational in case of an failure.
- Energy consumption should remain acceptable.
- The device should not produce distracting noises.
- In manual mode the device must comply with current standards.

5 Function analysis

The Function analysis gives an overview of the different tasks that are carried out when dynamically applying a multi shape light field during a surgical procedure. The function of creating the adaptive light field has been divided into several sub functions (f2-f8) to allow for individual design options instead of having to perform them with one single solution. The interaction between the surgeon and wound and between the surgeon and luminary aren't explained in detail as this is designed by other students in separate projects. It is assumed that the information coming from the surgeon about the desired light field is the only data that is needed for this study.

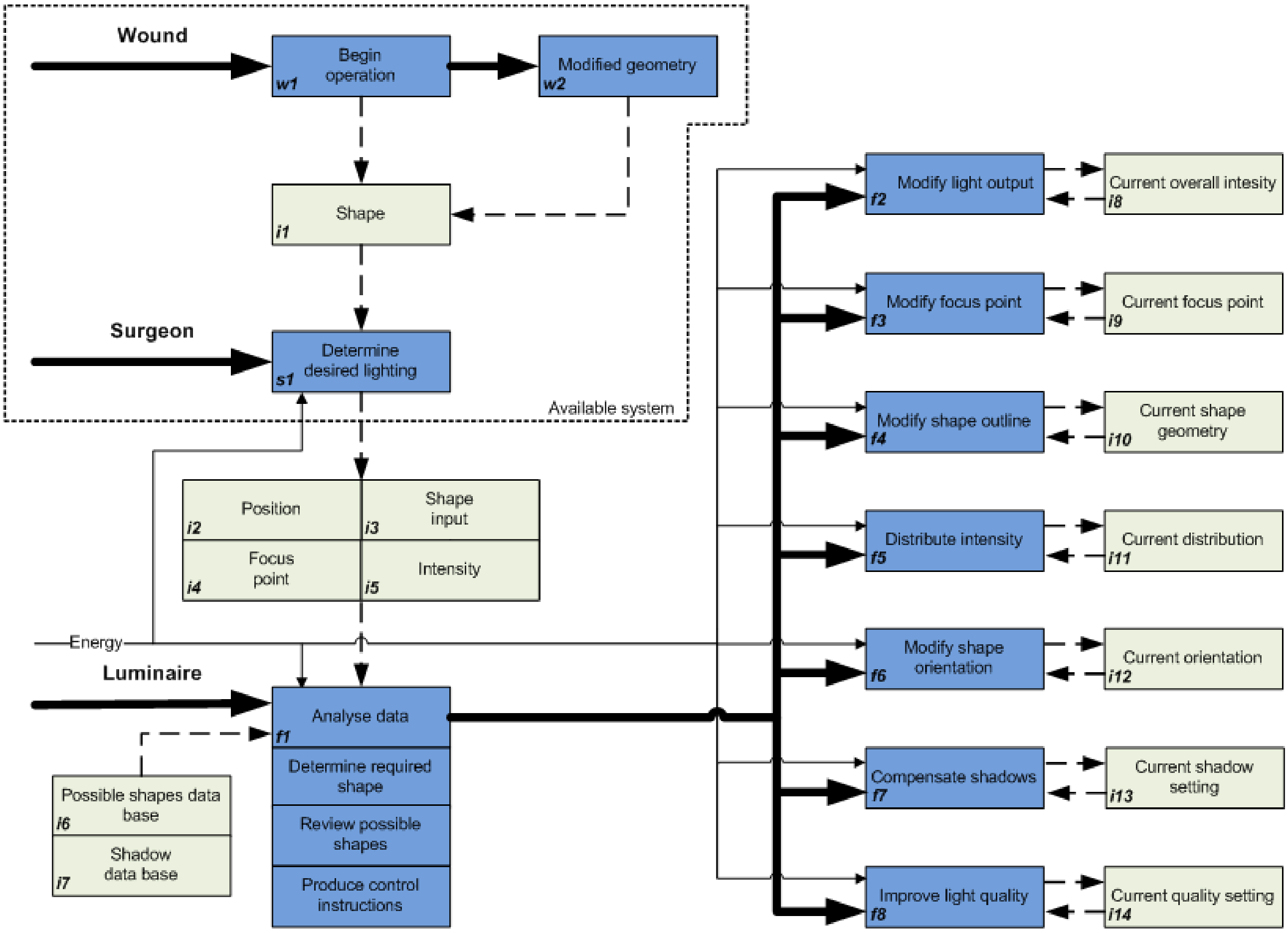


Figure 1: Function analysis scheme

5.1 About the scheme

The scheme shows three main subjects that play a role in the lighting process; the wound, the surgeon and the luminary. The functions that are performed by these subjects are shown in the blue squares. Functions belonging to the wound are identified with an "w" in the lower left corner of a function block. For the surgeon this is a "s" and for the luminary a "f".
Information flows are placed in the green blocks and are connected to the functions by striped lines. They are also identified by the letter "i" in the lower left corner.
The thin line labelled "energy shows which processes need a form of produced energy to function.

5.2 Blocks

w1 At the starting point of the operation the size of the operating area is determined. The wound area is still closed. The required size and shape of the light field is determined by a prediction of the wound shape during the procedure.

w2 During the procedure the wound geometry changes over time.

i1 Information about the wound is constantly going to the surgeon when he is looking at the wound.

s1 The surgeon needs to determine which lighting conditions he desires at the start of the operation and during the procedure. When he decides that lighting conditions need to change he will send information about what he wants to change to the luminary. This can be done using the designated controller, which is designed in a separate study, or he can use manual control.

i2 By using the control device, information is sent about how the wound is positioned in relation to the luminary.

i3 The desired outline of the shape is drawn using the control device.

i4 A desired distribution of the light field can optionally be indicated using the control device.

i5 An overall increase or decrease can be determined using the control device

f1 All the information received by the luminary coming from the control device needs to be analysed to determine how to command the luminaire. Determining the required shape will be necessary if the shape input is more complex than the luminaire can produce. The simplified shape is then compared with known possible light field shapes. When the final light field shape is determined, a set of instructions is produced by the CPU and is sent to the luminaire's controller.

i6 In the case of a feed forward controller a database or function is needed to determine which shapes and distributions are possible. In a feedback controller this information might come 'on the fly' from a separate system.

i7 To be able to reduce shadows it is also needed to have knowledge about how the shadows behave in certain configurations. This information might also come from a data base or from a separate system.

f2 This sub function sets the overall illumination strength to brighter or darker.

i8 Some methods of modifying the light output require information about the current state of the light output. Information about the difference between actual overall intensity and desired overall intensity is fed back to the luminary's CPU. An example is a system that uses a camera to monitor the light levels. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f3 In the case that the focus point is at another location than the current focus point, it needs to shift along the surgical area.

i9 Information about the difference between actual position and desired position is fed back to the luminary's CPU. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f4 The shape of the light field outline needs to be adapted to fit the required shape.

i10 Information about the difference between the actual shape and the desired shape is fed back to the luminary's CPU. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f5 The intensity distribution along the light field needs to be adapted to fit the required distribution.

i11 Information about the difference between the actual distribution and the desired distribution is fed back to the luminary's CPU. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f6 If the proper shape is being produced but it is not aligned properly with the wound it is needed to change it's orientation to fit the desired orientation.

i12 Information about the difference between actual orientation and desired orientation is fed back to the luminary's CPU. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f7 Reducing shadows might be a separate feature on the luminary and in that case need separate control.

i13 The information about the current shadows that are produced will be needed to provide proper compensation. This information block will be needed if a feedback system is used to control the function, else it can be omitted.

f8 In some cases it might be possible to improve the light quality further. A feedback feature is needed for this, which is not part of the system at this moment.

i14 Improvements are likely made using predefined settings. Information about which setting the device is in and which setting is needed will be fed back to the luminary's CPU. This information block will be needed if a feedback system is used to control the function.

6 Morphology

The following section covers several possible design solutions for the adaptable surgical luminaire. The focus in this design process is to come up with a design that is able to fulfil each of the sub-functions of the surgical luminaire in a suitable manner. Eight individual functions were identified in the function analysis. The last two functions, ”Compensate shadows” and ”Improve light quality”, will not be analysed at this point of the design process. This is decided to reduce the design complexity. First an overview is given of the individual sub functions and possible solutions.

6.1 Table of possible solutions

Table 1 shows the individual sub-functions of the adaptable surgical luminaire with on the right the possible solutions that will be analysed later on. There are several solutions that are able to fulfil several of the sub functions, so they will appear in the list more than once. A description of each of the individual solutions and how they should function is given below the table.

Function	No.	Solution
f1 Analyse data	f1.1	CPU
f2 Modify light output	f2.1	Controlled intensity light source
	f2.2	Block light
f3 Modify focus point	f3.1	Multiple directional light sources
	f3.2	Shape adaptable luminary surface
	f3.3	Shape adaptable back mirror
	f3.4	Directional multi mirror system
	f3.5	Position adaptable source reflector
f4 Modify shape outline	f4.1	Multiple directional light sources
	f4.2	Shape adaptable luminary surface
	f4.3	Shape adaptable back mirror
	f4.4	Controlled intensity for each light source
	f4.5	Directional multi mirror system
	f4.6	Nematic Phase Liquid Crystals
	f4.7	Adjustable blind
f5 Distribute intensity	f5.1	Multiple directional light sources
	f5.2	Shape adaptable luminary surface
	f5.3	Shape adaptable back mirror
	f5.4	Controlled intensity for each light source
	f5.5	Directional multi mirror system
	f5.6	Nematic Phase Liquid Crystals
f6 Modify shape orientation	f6.1	Multiple directional light sources
	f6.2	Shape adaptable luminary surface
	f6.3	Shape adaptable back mirror
	f6.4	Controlled intensity for each light sources
	f6.5	Directional multi mirror system
	f6.6	Nematic Phase Liquid Crystals
	f6.7	Move/Rotate light source

Table 1: Concept solutions overview

f1 Analyse data Important part of creating a functional device is being able to process the user input and create proper control commands. The user input from the surgeon held device consists of information about: shape position and orientation, shape outline, light field distribution and light intensity. This information needs to be processed.

f1.1 CPU Using a CPU to analyse the input data is the most feasible design choice given the complexity of the device and because the data received from the input device is also generated using a CPU. In the early stages of the design this will be done using a PC that is connected to the device, which provides ease of use and good flexibility. In further stages of the development the PC is likely to be replaced by an on board CPU. A manual bypass is needed to be able to operate the device in case of a system failure. This bypass will be designed when the system is in a later stage of development.

f2 Modify light output The overall brightness of the light field will need to be adjustable to accommodate a range of different lighting conditions. This is will adjust only the overall brightness level a will not involve a fundamental change in light field shape. This can be done by applying a gain to the lighting level, or by adding or subtracting an intensity value across the entire light field.

f2.1 Controlled intensity light source Reducing light output can simply be done with a simple dimming function.This can be done by reducing voltage, by pulse width modulation or by another technology.
Advantage of this is that it is likely possible to control this easily through the CPU without the need for mechanical systems. Disadvantage is that a light source should be used which allows this technology.

f2.2 Use Filter Placing a variable filter in between the luminary and the surgical field can be used to control the overall light output of the system. An example is a double sheet of polarizing material that is rotated relative to each other. Advantage is that this can be done without modifying the output of the light source directly. Disadvantage is that it is likely to become a rather complex mechanical system and it will generate internal heat from the blocked light.

f2.3 Use GOBO Using a "GOBO" or "goes before optics" is likely to have a similar result as using a filter. The difference is that a GOBO will be made of a certain material that blocks or redirects the light instead of altering its permeability to light.This means that it needs to change its general shape to reduce or increase the amount of light. Advantage is the same as with filtering with the addition of being able to reflect light instead of purely blocking it. Disadvantages are also largely the same as with filtering but with the addition of the possibly creating unwanted deformations in the light field.

f2.4Move light source Moving the light source closer or further away will also influence the amount of light that reaches the surgical field. Advantage is that the luminary system can remain unaltered with the exception of its position. Disadvantage is that the focus point an size of the light field will change. Also moving the light source is likely to be an unwanted procedure for such a simple task.

f2.5 Redirect light Redirecting light can be used to reduce the overall intensity if the light beam is directed away from the surgical field. Advantage is that it might be able to integrate it into a system that provides the general shape of the light field. Disadvantage is that it will require the change in direction of the light source or reflector. Removing a beam from the collection of light beams that build the light field might also cause inconsistencies inside the remaining light field.

f3 Modify focus point Changing the focus point will be needed to soften or sharpen the outline of the light field. This can be done by actually changing the convergence point of the light beam, or it can be imitated using diffuse light around the edge of the wound shape.

f3.1 Single directional LEDs Using an array of multiple LEDs that each have a set of degrees of freedom. Each LED will need to be actuated and controlled individually. Changing their position in an correlated manner can shift the convergence of the combined beams Advantage is being able to control the direction of each LED individually which will give a very high degree of control over the combined light field that is build up from the individual light fields Disadvantage is the need be able to control each of the LEDs which creates a highly complex system.

f3.2 Shape adaptable luminary surface Placing the LEDs inside a material sheet and changing the shape of this holder material. The change in shape of the holder material will cause the direction of the LEDs to change. The convergence of the combined beams will change in much the same way as with single controllable LEDs. Advantage is that this method links the degrees of freedom of several LEDs to that of the holder material. This greatly reduces the systems complexity. Disadvantage is that the capabilities of the final luminary will depend on how clever the design is made. Increasing capabilities will likely increase complexity.

f3.3 Shape adaptable back mirror Using a larger light source that projects its light field onto the surgical field by redirecting the light beam with the use of a mirror. This mirror needs to be able to change its shape or orientation in relation to the light source to modify the focus point of the projected light field. Advantage is that the light source can remain fixed in position and only a lightweight sheet of reflecting material needs to change its shape/position. Disadvantage is that it requires a strong large light source. Also the size of the luminary is like to increase due to the need for distance between the light source and mirror.

f3.4 Adaptable LED reflectors Each LED has a small reflector placed around the chip to direct the light forwards. Modifying the orientation of this reflector can alter the direction and beam focus of the LEDs. This can be done individually or in a combined manner. Advantage is that this will also give control over the beam width of each individual LED. Also the electronics of the LEDs could remain in place.

f3.5 Stationary back mirror with movable light This is a conventional way of surgical lighting and controlling the focus point. The back mirror has a parabolic shape. The distance of the light source to the mirror determines the focus point

f4 Modify shape outline Making the shape of the light field match the shape of the wound is one of the key functions in this new luminary design. It can be done by dimming or blocking portions of the light field that fall outside the desired area, or it van be done by redirecting light that would fall outside the desired area to the inside of the desired area.

f4.1 Multiple directional light sources Same technique as used to modify the focus point of the light field, with the difference that it is now used to modify the light field outline. Advantage is being able to control the direction of each LED individually which will give a very high degree of control over the combined light field that is build up from the individual light fields. Disadvantage is the need be able to control each of the LEDs which creates a highly complex system.

f4.2 Shape adaptable luminary surface Same technique as used to modify the focus point of the light field, with the difference that it is now used to modify the light field outline. Advantage is that this method links the degrees of freedom of several LEDs to that of the holder material. This greatly reduces the systems complexity. Disadvantage is that the capabilities of the final luminary will depend on how clever the design is made. Increasing capabilities will likely increase complexity.

f4.3 Shape adaptable back mirror Same technique as used to modify the focus point of the light field, with the difference that it is now used to modify the light field outline. Advantage is that the light source can remain fixed in position and only a lightweight sheet of reflecting material needs to change its shape/position. Disadvantage is that it requires a strong large light source. Also the size of the luminary is like to increase due to the need for distance between the light source and mirror.

f4.4 Controlled intensity for each light source Simply turning off a LED if it projects light at a part of the operating area that is not required will change the shape of the projected light field. Advantage is that it only requires a control instruction to function. Disadvantage is that some shapes might be hard to achieve with only switching LEDs and it requires overcapacity of the LED's output.

f4.5 Directional multi mirror system Placing a sheet of Nematic Phase Liquid Crystal material in between the light source and the operating area can be used to precisely block parts of the light beam where they are unwanted. The crystals will become impenetrable for the light when activated which can be done anywhere on its surface. Advantage is that it is also possible to block a part inside the light field without altering the light near the edge. Disadvantage is that it is a highly technical and complex system. It would be an experimental system.

f4.6 Nematic Phase Liquid Crystals A blinds system can be used to block unnecessary and/or unfavorable parts of the light field. These blinds can move in from the side and thereby blocking a part of the light field near the edge. Advantage is that the shape of the projected light field will depend on the shape that is moved in front of the luminary. Disadvantage is that it requires mechanical masks that will need to become more complex if many different light field shapes are required.

f5 Distribute intensity A second key feature of the new luminaire design will be the ability to distribute the light over the desired shape. This means for example that an elongated wound will be able to have an even light distribution over the entire length of the wound.

f5.1 Multiple directional light sources Same technique as used to modify the focus point and shape outline of the light field (3.1,4.1), with the difference that it is now used to distribute the intensity inside the light field. Advantage is being able to control the direction of each LED individually which will give a very high degree of control over the combined light field that is build up from the individual light fields Disadvantage is the need be able to control each of the LEDs which creates a highly complex system.

f5.2 Shape adaptable luminary surface Same technique as used to modify the focus point and shape outline of the light field (3.2,4.2), with the difference that it is now used to distribute the intensity inside the light field. Advantage is that this method links the degrees of freedom of several LEDs to that of the holder material. This greatly reduces the systems complexity. Disadvantage is that the capabilities of the final luminary will depend on how clever the design is made. Increasing capabilities will likely increase complexity.

f5.3 Shape adaptable back mirror Same technique as used to modify the focus point and shape outline of the light field (3.3,4.3), with the difference that it is now used to distribute the intensity inside the light field. Advantage is that the light source can remain fixed in position and only a lightweight sheet of reflecting material needs to change its shape/position. Disadvantage is that it requires a strong large light source. Also the size of the luminary is like to increase due to the need for distance between the light source and mirror.

f5.4 Controlled intensity for each light source Same technique as used to modify the shape outline of the light field (4.4), with the difference that it is now used to distribute the intensity inside the light field. Advantage is that it only requires a control instruction to function. Disadvantage is that some distributions might be hard to achieve with only switching LEDs.

f5.5 Same technique as used to modify the shape outline of the light field (4.5), with the difference that it is now used to distribute the intensity inside the light field. Advantage is that it is also possible to block a part inside the light field without altering the light near the edge. Disadvantage is that it is a highly technical and complex system. It would be an experimental system.

f5.6 Nematic Phase Liquid Crystals

f6 Modify shape orientation **f6.1 Multiple directional light sources** Combined solution for with function 3.1,4.1 and 5.1. Advantage is being able to control the direction of each LED individually which will give a very high degree of control over the combined light field that is build up from the individual light fields Disadvantage is the need be able to control each of the LEDs which creates a highly complex system.

f6.2 Shape adaptable luminary surface Same technique as used to modify the focus point, shape outline and distributing the intensity of the light field (3.2,4.2,5.2), with the difference that it is now used to modify the orientation of the light field. Advantage is that this method links the degrees of freedom of several LEDs to that of the holder material. This greatly reduces the systems complexity. Disadvantage is that the capabilities of the final luminary will depend on how clever the design is made. Increasing capabilities will likely increase complexity.

f6.3 Shape adaptable back mirror Same technique as used to modify the focus point, shape outline and distributing the intensity of the light field (3.3,4.3,5.3), with the difference that it is now used to modify the orientation of the light field. Advantage is that the light source can remain fixed in position and only a lightweight sheet of reflecting material needs to change its shape/position. Disadvantage is that it requires a strong large light source. Also the size of the luminary is like to increase due to the need for distance between the light source and mirror.

f6.4 Controlled intensity for each light source Same technique as used to modify the shape outline of the light field and distributing the intensity of the light field (4.4,5.4), with the difference that it is now used to modify the orientation of the light field. Advantage is that it only requires a control instruction to function. Disadvantage is that some orientations might be hard to achieve with only switching LEDs.

f6.6 Nematic Phase Liquid Crystals Same technique as used to modify the shape outline of the light field and distributing the intensity of the light field (4.5,5.5), with the difference that it is now used to modify the orientation of the light field. Advantage is that it is also possible to block a part inside the light field without altering the light near the edge. Disadvantage is that it is a highly technical and complex system. It would be an experimental system.

f6.7 Move/Rotate light source To move/rotate the light field, it is possible to just move/rotate the luminary as a whole so the light field fits better over the desired orientation. Advantage is that this can be a separate system and therefore will not interfere with other functions. Disadvantage is that it will change the position of the luminary in space, thereby increasing the change of bumping into objects. Also will it make the luminary more complex compared to when it is done using already present systems.

6.2 Concept selection

In the following section an analysis is made to come to the best solution for the surgical luminaire system. This is done by combining the individual solutions for each sub-function. In table 2 an overview is given that shows for each solution with which other solution it is able to function in parallel. A green block indicates it is possible, a red block indicates it is not possible and a white block with an o inside indicates that it is essentially the same solution.

		f2		f3					f4							f5						f6						
		1	2	1	2	3	4	5	1	2	3	4	5	6	7	1	2	3	4	5	6	1	2	3	4	5	6	7
f2	1	o																										
	2		o																									
f3	1			o					o							o						o						
	2				o					o							o						o					
	3					o					o							o						o				
	4						o						o							o						o		
	5							o																				
f4	1			o					o							o						o						
	2				o					o							o						o					
	3					o					o							o						o				
	4											o							o						o			
	5						o						o							o						o		
	6													o							o							
	7														o													
f5	1			o					o							o						o						
	2				o					o							o						o					
	3					o					o							o						o				
	4											o							o						o			
	5						o						o							o						o		
	6													o							o						o	
f6	1			o					o							o						o						
	2				o					o							o						o					
	3					o					o							o						o				
	4											o							o						o			
	5						o						o							o						o		
	6																				o						o	
	7																											o

Table 2: Concept choice chart

6.3 Concept reduction

Because table 2 gives many different concept options, an analysis of the different solutions is done to see if some of the solutions can be removed from the thorough analysis which is done later on. The results are given in table 3. All solutions < 20 are removed from the table, which results in the reduced Concept choice chart of table 4.

Solution	Occurs	Complexity 10	Functional performance 10	Efficiency 6	Space requirements 6	**32**
Controlled intensity light source	f1.1	10	10	6	6	**32**
Block light	f1.2	6	7	3	4	**20**
Multiple directional light sources	f3.1 f4.1 f5.1 f6.1	5	9	5	2	**21**
Shape adaptable luminary surface	f3.2 f4.2 f5.2 f6.2	8	8	5	5	**26**
Shape adaptable back mirror	f3.3 f4.3 f5.3 f6.3	4	5	5	4	**18**
Directional multi mirror system	f3.4 f4.5 f5.5 f6.5	3	7	5	2	**17**
Position adaptable source reflector	f3.5	8	6	6	4	**24**
Controlled intensity for each light source	f4.4 f5.4 f6.4	9	7	5	6	**27**
Nematic Phase Liquid Crystals	f4.6 f5.6 f6.6	7	9	3	4	**24**
Adjustable blind	f4.7	5	5	4	2	**17**
Move/rotate light source	f6.7	9	8	5	3	**25**

Table 3: Concept reduction scores

		f2		f3			f4				f5				f6				
		1	2	1	2	5	1	2	4	6	1	2	4	6	1	2	4	6	7
f2	1	o																	
	2		o																
f3	1			o			o				o				o				
	2				o			o				o				o			
	5					o													
f4	1			o			o				o				o				
	2				o			o				o				o			
	4								o				o				o		
	6									o				o					
f5	1			o			o				o				o				
	2				o			o				o				o			
	4								o				o				o		
	6									o				o				o	
f6	1			o			o				o				o				
	2				o			o				o				o			
	4								o				o				o		
	6													o				o	
	7																		o

Table 4: Reduced concept option chart

6.4 Concept analysis 1st round

The reduced concept option chart is used to combine the individual remaining solutions into five main concepts. These are based on the four remaining main principles without combining these principles within a concept. The concept that uses nematic phase liquid crystals has two forms since it can be done using both options for function f2. The possibility of adding a system that rotates the light source (function f6) to the concept also is left out of this first analysis since each of the solutions all ready should be able to modify its shape orientation. Adding extra systems will be reviewed at a later stage. Table 5 gives the concepts and shows which individual solutions that are used in each concept. For each of these concepts is assessed how well it is able to fulfil the individual sub-functions The results af this analysis is shown is table 6. The results show that there is no concept that really stands out. The Nematic phase concepts score pretty well on the functionalities that involve control over and flexibility of the light distribution, but areas like the reduction of shadows and use of proven technology problematic. Since the concepts 4.1 and 4.2 can not be integrated with other systems that could compensate these short comings, these two concepts are not chosen for the design. The first concepts, that all use arrays of multiple light sources, are able to be combined with each other or with additional systems.

Concept	Function		Solution	
1	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.1	Multiple directional light sources
	f4	Modify shape outline	4.1	Multiple directional light sources
	f5	Distribute intensity	5.1	Multiple directional light sources
	f6	Modify shape orientation	6.1	Multiple directional light sources
2	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.2	Shape adaptable luminary surface
	f4	Modify shape outline	4.2	Shape adaptable luminary surface
	f5	Distribute intensity	5.2	Shape adaptable luminary surface
	f6	Modify shape orientation	6.2	Shape adaptable luminary surface
3	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.5	Position adaptable source reflector
	f4	Modify shape outline	4.4	Controlled intensity for each light source
	f5	Distribute intensity	5.4	Controlled intensity for each light source
	f6	Modify shape orientation	6.4	Controlled intensity for each light source
4a	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	-	No system required
	f4	Modify shape outline	4.6	Nematic Phase Liquid Crystals
	f5	Distribute intensity	5.6	Nematic Phase Liquid Crystals
	f6	Modify shape orientation	6.6	Nematic Phase Liquid Crystals
4b	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.2	Block light
	f3	Modify focus point	-	No system required
	f4	Modify shape outline	4.6	Nematic Phase Liquid Crystals
	f5	Distribute intensity	5.6	Nematic Phase Liquid Crystals
	f6	Modify shape orientation	6.6	Nematic Phase Liquid Crystals

Table 5: Concepts overview

Functional area	Criteria	F	Concepts 1	2	3	4a	4b
Modify light output (f2)	Step resolution	10	10	10	10	9	8
	Output accuracy	8	8	8	8	7	6
			(18)	(18)	(18)	(16)	(14)
Modify focus point (f3)	Achieve sharp edge	10	8	7	6	10	10
	Achieve blurred edge	8	6	5	4	8	8
	Uniform light distribution	10	8	7	4	9	9
	Reduce shadows	8	8	7	7	3	3
			(30)	(26)	(21)	(30)	(30)
Modify shape outline (f4)	Shape diversity	8	7	6	4	8	8
	Shape accuracy	10	9	8	4	10	10
	Uniform light distribution	10	8	7	5	9	9
	Reduce shadows	8	8	7	7	3	3
			(32)	(28)	(20)	(30)	(30)
Distribute intensity (f5)	Create light gradients	10	8	7	6	10	10
	Uniform light distribution	10	8	7	5	9	9
	Reduce shadows	8	8	7	7	3	3
			(24)	(21)	(18)	(22)	(22)
Modify shape orientation (f6)	Step resolution	10	8	7	4	10	10
	Accuracy	8	7	5	4	7	7
	Maintain shape form	6	4	3	3	6	6
	Reduce shadows	8	8	7	7	3	3
			(27)	(22)	(18)	(26)	(26)
	Total	**150**	**131**	**115**	**95**	**124**	**122**
	Score	100%	87%	77%	63%	83%	81%

Table 6: Concept score chart, functional criteria

			Concepts				
General area	**Criteria**	**F**	**1**	**2**	**3**	**4a**	**4b**
Complexity	Few moving parts	10	2	8	10	8	9
	Use of proven technology	10	8	8	10	2	2
	Control complexity	5	2	3	5	3	3
	Manually controllable	8	3	5	6	2	2
			(15)	(24)	(31)	(15)	(16)
Designability	Possible to make CAD model	5	4	4	5	2	2
	Possible to optimize design	8	7	7	4	3	3
	Possible to build mode	4	3	4	4	1	1
			(14)	(15)	(13)	(6)	(6)
	Total	**50**	**29**	**39**	**44**	**21**	**22**
	Score	100%	58%	78%	88%	42%	44%

Table 7: Concept score chart, general criteria

	Concepts				
	1	**2**	**3**	**4a**	**4b**
Functional area score	87%	77%	63%	83%	81%
General area score	58%	78%	88%	42%	44%
Combined score	73%	78%	76%	63%	63%

Table 8: Concept score overview

6.5 Concept analysis 2nd round

Concept 2, which uses a shape adaptable luminary surface to carry out most of the individual sub functions, showed the best balance between both the functional requirements and the general requirements. To see if it is possible to improve this concept further a new analysis is done, but this time also some possible hybrid forms of several solutions will be introduced. A combination of two solutions might for example boost performance in the functional area while maintaining performance in the general area so the combined score could improve. To test this concept 2 is taken as a basis for 3 new concepts that make use of possible combinations shown in table 4.

Concept	Function		Solution	
	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.2	Shape adaptable luminary surface
2a			3.5	Position adaptable source reflector
	f4	Modify shape outline	4.2	Shape adaptable luminary surface
	f5	Distribute intensity	5.2	Shape adaptable luminary surface
	f6	Modify shape orientation	6.2	Shape adaptable luminary surface
	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.2	Shape adaptable luminary surface
	f4	Modify shape outline	4.2	Shape adaptable luminary surface
2b			4.1	Multiple directional light sources
	f5	Distribute intensity	5.2	Shape adaptable luminary surface
			5.1	Multiple directional light sources
	f6	Modify shape orientation	6.2	Shape adaptable luminary surface
			6.1	Multiple directional light sources
	f1	Analyse data	1.1	CPU
	f2	Modify light output	2.1	Controlled intensity light source
	f3	Modify focus point	3.2	Shape adaptable luminary surface
	f4	Modify shape outline	4.2	Shape adaptable luminary surface
2c			4.4	Controlled intensity for each light source
	f5	Distribute intensity	5.2	Shape adaptable luminary surface
			5.4	Controlled intensity for each light source
	f6	Modify shape orientation	6.2	Shape adaptable luminary surface
			6.4	Controlled intensity for each light source

Table 9: Concepts 2

Functional area	Criteria	F	Concepts 2a	2b	2c
Modify light output (f2)	Step resolution	10	10	10	10
	Output accuracy	8	8	8	8
			(18)	(18)	(18)
Modify focus point (f3)	Achieve sharp edge	10	8	8	8
	Achieve blurred!40! edge	8	7	7	6
	Uniform light distribution	10	8	9	8
	Reduce shadows	8	7	7	7
			(30)	(31)	(29)
Modify shape outline (f4)	Shape diversity	8	6	7	7
	Shape accuracy	10	8	9	8
	Uniform light distribution	10	8	8	8
	Reduce shadows	8	7	8	7
			(29)	(32)	(30)
Distribute intensity (f5)	Create light gradients	10	8	9	8
	Uniform light distribution	10	8	9	8
	Reduce shadows	8	7	8	7
			(23)	(26)	(23)
Modify shape orientation (f6)	Step resolution	10	7	8	7
	Accuracy	8	5	7	6
	Maintain shape form	6	3	4	4
	Reduce shadows	8	7	8	7
			(22)	(27)	(24)
	Total	**150**	**122**	**134**	**124**
	Score	100%	81%	89%	83%

Table 10: Concept score chart, functional criteria 2nd round

General area	Criteria	F	Concepts 2a	2b	2c
Complexity	Few moving parts	10	3	2	8
	Use of proven technology	10	7	8	8
	Control complexity	5	1	2	3
	Manually controllable	8	3	3	4
			(14)	(15)	(23)
Designability	Possible to make CAD model	5	3	4	4
	Possible to optimize design	8	6	7	7
	Possible to build mode	4	2	2	4
			(11)	(13)	(15)
	Total	**50**	**25**	**28**	**38**
	Score	100%	50%	56%	76%

Table 11: Concept score chart, general criteria 2nd round

Table 12 Gives an overview of the final results of the 3 new concepts. Concept 2c offers the best results of the three new concepts and provides an improvement over the original concept 2 from the first design round. This means that only adding control over the intensity of the individual LEDs will improve the performance of the shape adaptable luminary surface, but adding additional systems like reflectors or directional LEDs will not.

	Concepts 2a	2b	2c
Functional area score	81%	89%	83%
General area score	50%	56%	76%
Combined score	66%	73%	80%

Table 12: Concept score overview 2nd round

6.6 Design choice

The chosen design is a system that uses a shape adaptable surface that has the light sources attached to it. The intensity of these light sources can be controlled. This device will receive the input image and translate this into a new system state that makes the new light field possible. A very simple and elegant solution for the bendable surface is using strips that hold the light sources. Placing these strip is a radial alignment creates a system that can move the spots over a large surface area beneath the luminaire. An example about what such a system will look like can be seen in figure 2. The strips can bend to modify the direction of the LEDs. The angle of the strips must be adjustable to position the light field on the surface.

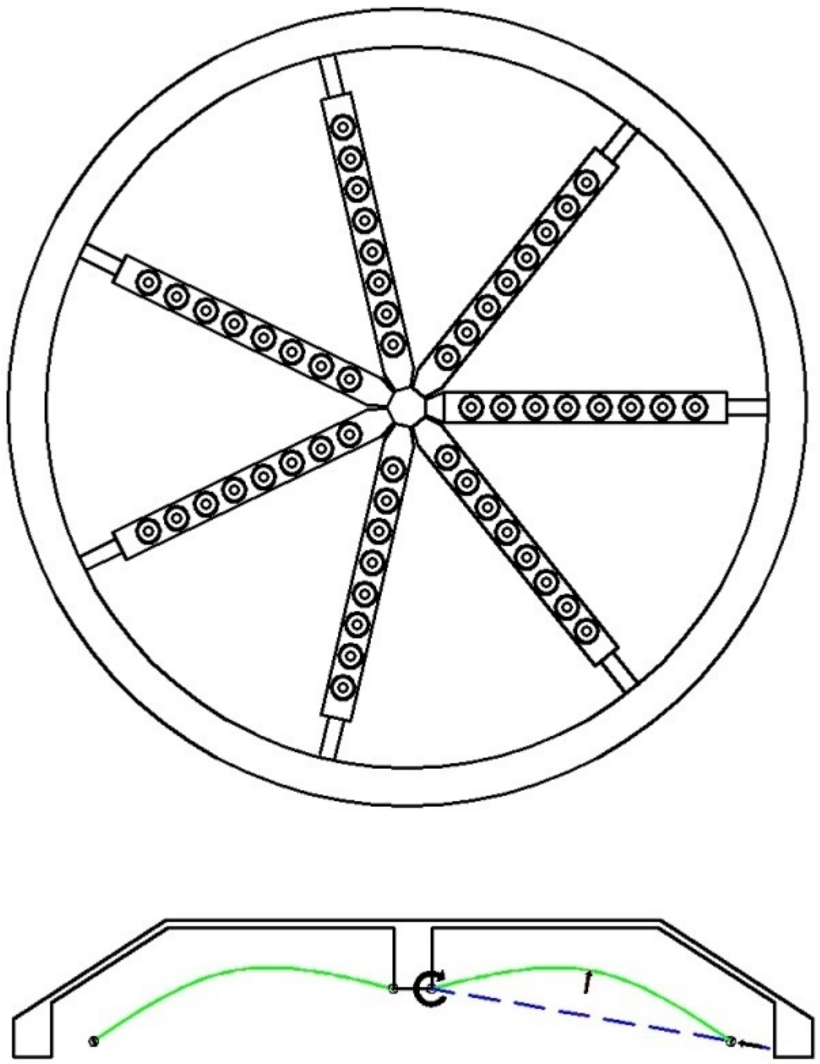


Figure 2: Bottom view and cross section of a luminaire that uses bendable strips.

7 Preliminary design

During the concept analysis a design solution was chosen that makes use of multiple LEDs as light source. These LEDs are mounted on flexible strips. These strips will be used to alter the direction of the LEDs which are attached to its surface. This way it is possible to control the direction of several LEDs by manipulating a single strip. By combining multiple strips it is possible to create light fields that have more complex shapes. It is needed to adjust the intensity of each LED individually in order to maintain a good light distribution inside the combined light field. This means that the system consists of many light sources that are placed in several subsystems that will have to work together to create an optimal light field. To achieve a functional system it is important to investigate the effects of the different design choices.

7.1 Current situation

The surgical environment is a dynamic setting in which many different elements are changing over time. To be able to develop a system that can compete with current systems, it is needed that the luminaire can cope with most common surgical conditions at least as well as current systems can. Many classic surgical luminaries make use of a single high intensity light source that is directed upwards towards a reflecting surface which projects the light downward onto the operating area. This method creates a typical beam shape that is wide at the top, has a narrow waist in mid-air and then widens to the spot diameter. This narrow waist is an advantage because it gives room for the surgeon to manoeuvre without disrupting the light field. Therefore it is important that the newly developed system also incorporates similar functionality.

7.2 LED functionality

The final luminaire design will produce a light field that consists of many small light spots that together form one evenly distributed large light field. Each spot will have to partly overlap with their closest neighbour to be able to create a smooth transition throughout the light field.

7.2.1 LED properties

The LED is a fairly simple light source. The following properties are of main interest when looking of the produced light field. Figure 4 show a spot shape with a peak power of 1 cd and a spot width of 1 mm.

Power The power value of an LED that is given by the manufacturer, is given in lumen. This is a value for the total amount of spectral energy that is created by the LED. The spectral energy is not evenly distributed and will be focussed with a lens. Therefore other values are needed to specify the shape of the beam. Peak power is often meant when the term power is used for a spot. This is the maximum value in the middle of the spot. This value is given in lux.

Distribution The projected spot has a bell shaped light distribution, see figure 4. The total luminous power of the LED is equal to the volume of this shape. The distribution becomes wider and less intense as the distance to the illuminated surface gets larger, but the total volume stay te same.

FWHM The size of the created light spot is not an obvious value which is caused by the fact that the light distribution of an LED is a 3D Gaussian. This means that most light falls in a small area, but some light rays will be directed farther away from the centre of the spot. The full width half maximum is used to give a definition of the size of the spot. It is the diameter of the area of the spot where the light intensity is more than 50% of the maximum intensity value.

Beam angle Because the light that comes from the LED is divergent will the FWHM of the spot depend on the distance of the surface to the source. Each LED-lens combination gives the angle of divergence to be able to calculate the size of the spot at a certain distance. Figure 3 gives the relationship between the angle and the width of the spot. The luminaire will be used mostly around 1 meter. The red lines show the effect when the distance to the surface decreases or increases. Because the final light field will be created with many light spots, is it likely that the used LEDs will be fitted with a lens system that generates a very narrow beam.

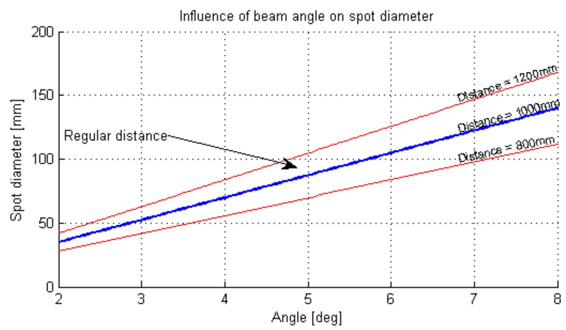


Figure 3: Spot width / beam angle relationship at different projection distances

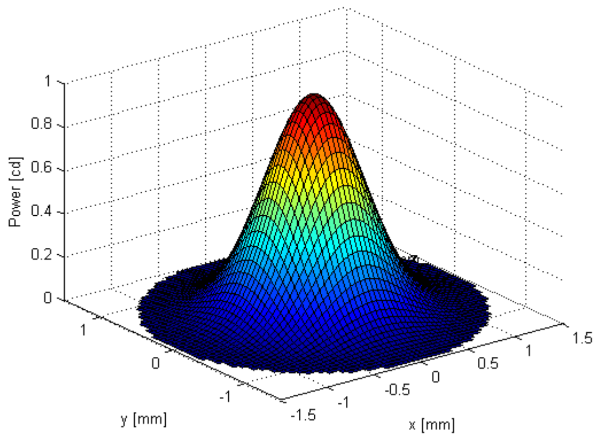


Figure 4: Basic spot shape

7.2.2 Angled surface

When the spot hits a surface at an angle, the shape of the spot will become oval and the centre point of the spot will shift slightly away from the middle, as can be seen in figure 5. The cross in the middle of the spot indicates the position of the centre for both angles. The elliptical shape is very obvious for an angle of 45 deg, but under normal conditions is such a large angle for this luminaire system unlikely. A maximum angle of around 25 is more likely if the luminaire is placed in it's normal position straight above the target shape. Figure 11 and 11 give the relation between the angle and the spot shape and centre shift. The deformation remains low at the small angles that the system will encounter. Because using this effect would increase the calculation complexity, is the ellipse effect not incorporated in the calculations.

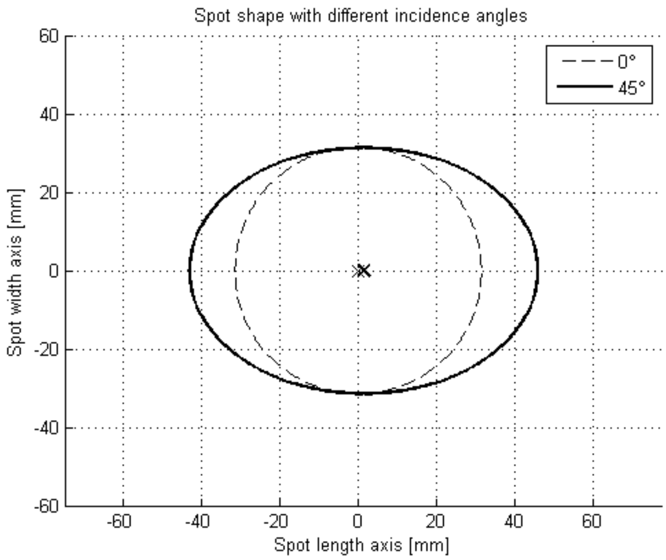


Figure 5: Spot shape at angle

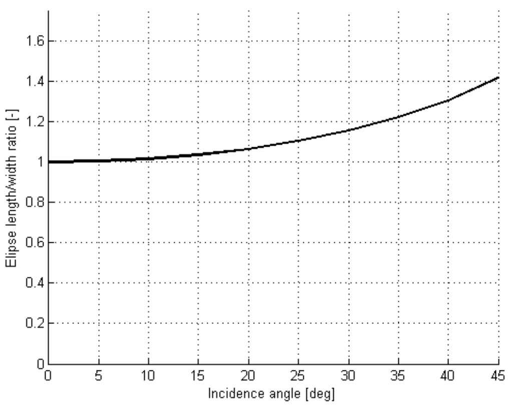


Figure 6: Ellipse ratio at different angles

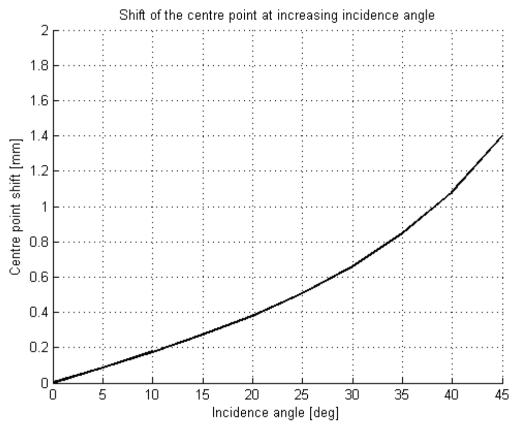


Figure 7: Centre shift at different angles

7.3 Strip functionality

Each strip has two parameters that determine it's functionality. The first parameter is the curvature. By curving the strip it is possible to control the spread of the focus points of the individual LEDs.

The second parameter is the orientation of the strip. This orientation is controlled by the angle between the horizontal plane and the line that intersects both endpoints of the strip. By changing this angle it is possible to position the combined light field along a linear path. The combined light field will be a result from the curvatures and angles of the individual strips and the intensity of each LED.

7.3.1 Curvature method

The direction of the LEDs are determined by the deformation of the strip. The shape of this deformation depends on the construction of the strip and the way it is actuated. To reduce construction complexity and to keep the calculations simple, a very basic deformation method was chosen for this project. Each strip will be connected to the luminaire body by a hinge at both ends. Deformation is initiated by either moving the end points together, or by moving a point in the middle of the strip upwards. Both methods will result in a similar deformation, but both have their own strengths and weaknesses.

Endpoint distance control The method of moving the endpoints will make it possible to let the rest of the strip move freely. It is also possible to carry out the adjustments of the strip curvature and the strip angle with only one actuator when this method is chosen. A disadvantage is that the relationship between the endpoint distance and strip curvature is non-linear, which means that situations with very little curvature are difficult to control. Figure 8 shows the deflection of the middle of a 400 mm long strip when the endpoints are moved closer together. At 400 mm the strip is flat and at 398 mm the curvature is all ready around 18 mm. So moving the endpoints 2 mm closer together has a large effect on the strip.

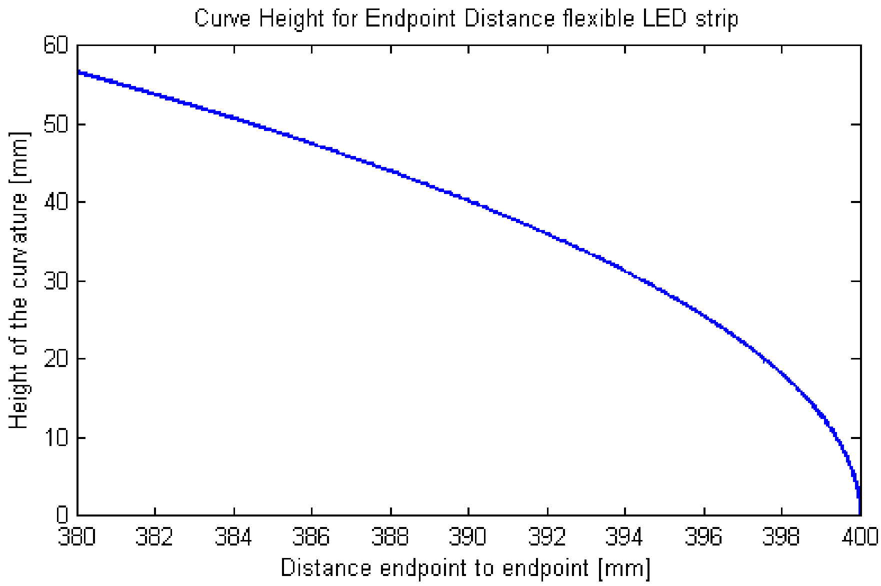


Figure 8: Relationship between endpoint distance and curve height

Mid point control The method where the middle of the strip is actuated has the advantage that the curve height is controlled directly and which means that an actuation error is not amplified close to 400 mm. It is also possible to stabilise the system against vibrations and unwanted deformations, because the strip is handled in the middle as well as at the end points. A disadvantage is that the required deformation might be hindered if the actuation system is designed poorly.

7.3.2 Strip deformation

Each strip can be modelled as a thin straight beam that is supported in its endpoints. The hinge on the proximal end of the strip allows rotation and the hinge on the distal end allows both rotation and horizontal displacement. As the ends of the strip start to move together, the strip curves upwards.

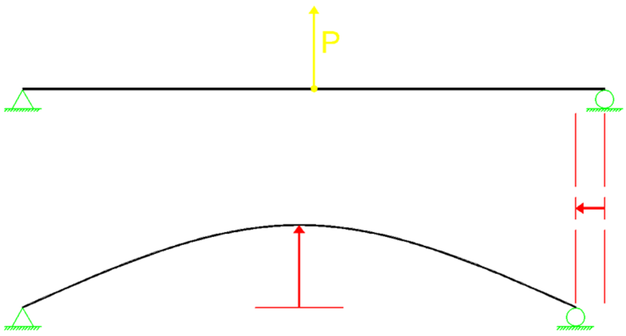


Figure 9: Bending shape with a central point load

The shape of the deformation is similar to a scenario where a concentrated load is applied in the middle of the strip in perpendicular direction. The deformation formulas for a beam under similar loading conditions give equation 1 for the deflection of a point somewhere on the strip.

$$y_{strip}(x) = P\frac{x}{48EI}(3{L_{strip}}^2 - 4x^2) \tag{1}$$

The directions of the LEDs is perpendicular to the surface of the strip, so the derivative of this function gives the direction of the LED somewhere on the strip. During the optimisation process, the position and direction of each LED is calculated many times. Therefore it is desirable to simplify this formula to speed up the calculations. The strip in the final design will be thin compared to it's length. In that case the deformation will take a shape that is very close to the shape of the positive half of a sine wave. Figure 10 shows the deformation shape compared to a sine along with the errors between the two. The derivative is also compared. The error in the direction of the LED is amplified during use by the distance between the LED and the surface. This effect is acceptable at this moment because the values are so low, that it will not have a large effect on the way the strip behaves. Other effects like gravity will affect the bending shape as well in a real situation. Therefore it will be necessary to make a more comprehensive model of a strip when the final design is completed.

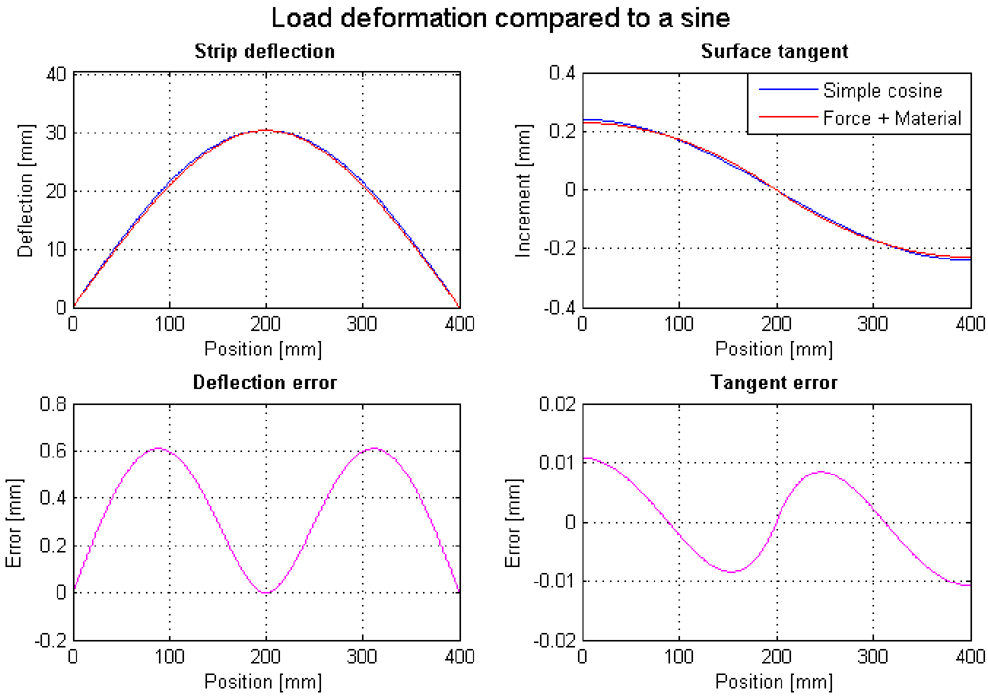


Figure 10: Comparison of the deformation cause by a central force and a sine. Strip dimensions:25*1*400[mm] Force:10[N] E:210[GPa]

7.3.3 LED positions

When a strip curves upwards, an LED that is attached to the surface follows this movement. Since the LED is fixed to the strip, the location of the LED is determined by the curve length of the strip section which starts at the hinge point and goes up to the position of the LED. This curve length is calculated with the integral in equation 2. H_{strip} is the height of the curve in the middle and W_{strip} is the distance between the two endpoints. The value of x is then determined where L is equal to the distance of the LED on a un curved strip. When the x-position is known the y-position can be found by filling in equation 3.

$$L = \int_0^x \sqrt{1 + (H_{strip} * \cos(\frac{\pi}{W_{strip} * x}) * \frac{\pi}{W_{strip}})^2} \tag{2}$$

$$H(x) = H_{curve} * sin(\frac{\pi}{EndPD} * x) \tag{3}$$

7.3.4 Combined beam shape

Each LED has a specific direction in which it emits it's light. This creates a line that determines where the brightest point of the spot will be located on an intersecting surface. These lines need to intersect to create the desirable narrow waist in the area between the luminaire and the surface.
When the strip curves the direction of the individual LEDs are altered and the lines start to intersect. The distance of the intersecting point of two LEDs decreases as the curvature increases. Because of the sine shaped curvature there will not be a true focus point where all directional lines intersect. The effect can be seen in figure 11. The green dots indicate where two opposite lines intersect. For curve

heights larger than 25 mm the intersecting lines create a waist somewhere between the surface an the luminaire. This waist is desirable because it gives room to the working area of the surgeon where no light will be blocked. Because the lines do not intersect the final light field will always be slightly larger than a single spot.

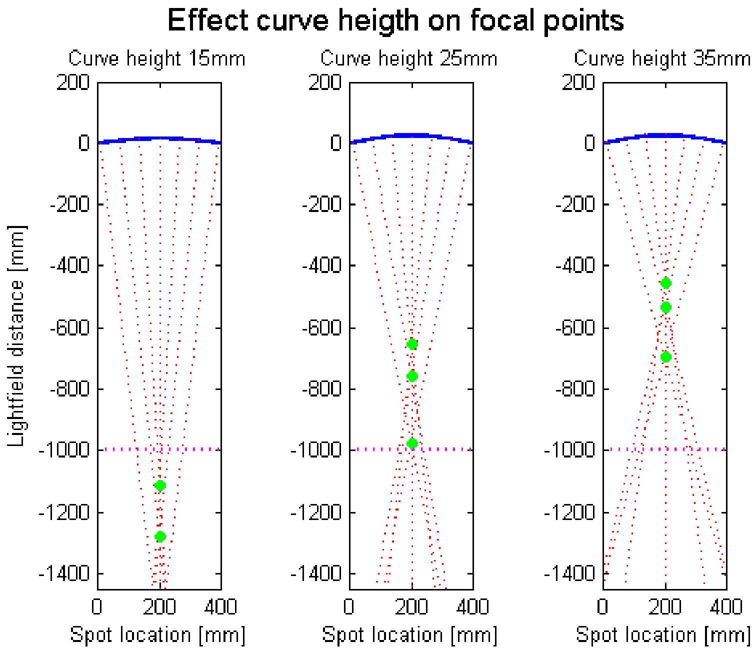


Figure 11: Effect of strip curvature on LED focus points

7.3.5 Strip angle

To move the combined light field of a single strip inside the total light field, it is needed to alter the angle of the strip. Figure 12 gives a view of this functionality. Modifying the angle moves the distal point of the strip up or down. This change in orientation modifies the spatial location and direction of the LEDs. The primary effect is that the locations of the projected spots is shifted along the surface. Another effect is that the angle of incidence changes for each of the LEDs. For some LEDs the angle increases and for other LEDs it decreases. This means that the elliptical shape of the spots changes. A 3rd effect is that the distance to the target surface is altered. The LEDs on the distal end of the strip are at a greater distance than the LEDs on the proximal end. LEDs that are further away will have a lower peak intensity and a wider spot diameter. The functionality of being able to modify the locations of the spots plays a primary role in the optimisation process. The secondary effects of an elliptical spot shape and the change in spot diameter are not used in the optimisation. Incorporating these effects would mean a major increase in computational complexity with only minor effects on the resulting outcome.

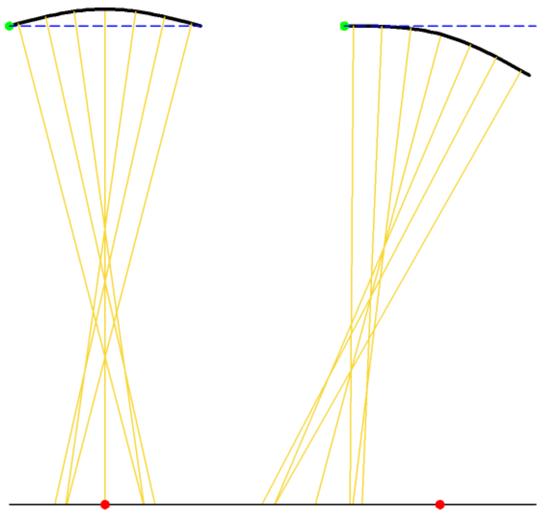


Figure 12: Effect of strip angle on LED focus points

7.4 Non-simplified situation

The modelled system is a simplification of the real life situation in which the strip must function. The following section addresses several of these simplifications

Change in distance The distance between an LED and the surface changes as the angle of the strip changes. When this distance gets shorter, then the spot width will decrease. This effect is not taken into account in the current calculations.

Deformation shape The shape of the deformation has been simplified to the shape of a sine. Although this shape comes very close to the deformation that follows from the calculations that make use of the material properties, there will be a slight difference which will produce an error for the direction of the LEDs.

Gravity The modelled strip does not take into account the effect of gravity on the deformation. The mass of the strip and the attached components play a role in the real situation. A more complex model can be used to calculate the deformation, but this will require more information about the system. For example how many LEDs are going to be used, how much they weigh and the direction of gravity as a result of the orientation of the strip.

Strip modifications The strip has a uniform cross-section along its entire length. If it is necessary to drill holes in the strip to be able to attach the LEDs, then this will affect the shape of the deformation. Minimizing this effect can be achieved by leaving the strip intact as much as possible.

LED alignment errors Each LED is assumed to be directed perpendicular to the strip surface. In reality there will be alignment errors that cause an error in the final spot location. A small error can have a large effect because the light field will be projected at a relatively large distance. It will be necessary to design a LED mounting construction to compensate for this.

8 Calculations

Projecting an adaptable light field onto the working area to achieve a closer match with the shape of the wound will unavoidably increase the complexity of the system compared to a standard light field. To make sure that this increase in complexity does not mean that the task of the human operator becomes more complex, is it necessary to perform tasks automatically by the luminaire. The following list gives an overview of some of the tasks that need to be performed by the luminaire system.

- Input calculations
  - Image processing
  - Shape handling
- Strip shape calculations
  - Strip curvature
  - Strip angle
  - LED positions
  - LED orientations
  - Resulting spot locations
- Optimization
  - Optimal spot positions
  - Spot brightness

8.1 User input

Current luminary systems have very basic controls to determine the shape of the light field. To come to an acceptable lighting condition the surgeon has the ability to position the luminaire as well as set the intensity and the width of the light field. Positioning the system is done by manually pushing and pulling the luminaire into the proper location. Adjusting the intensity and the width is done by pressing buttons on a console. The way the luminaire is positioned will not be addressed in this study, but the ability to control the shape of the light field will. To be able to add control over the light field shape, additional input information is needed. This information must come from the surgeon and it is important that feeding this information is easy to interpret.In a parallel study a hand held device was developed that can be used to record this wound shape (4). The device consists of a thin rod with a tip that is used to trace the wound. Several infra-red LEDs are located at the other end of the rod. The spatial location of these LEDs can be recorded using infra-red sensory technology. This sensing technology can be incorporated in the luminaire. Besides the shape of the light field it will also possible to set the desired intensity of the light field.

8.1.1 Processing user input

The traced outline of the desired light field shape has to be transformed into a usable image. Several modifications of the line segment are needed before it can be used as a system input.

Closing the shape It is needed to close the open ends of the line segment to form a proper shape outline. Assuming that the input has been properly executed, then the ends should be fairly close to each other. An algorithm needs to be developed that is able to carry out this task. Complexities like overlapping segment ends need to be corrected.

Flattening image In practice the outline will be a three dimensional shape. To simplify calculations the shape has to be projected onto a flat surface. If a single point source was used, then this projection would be fairly easy. However the luminaire consists of multiple point sources, which means that several projections are combined. This will unavoidably cause a change in the way the final light field is projected on the three dimensional surface. For input shapes that have much variation in the height of the input shape, a larger variation can be expected. The extend of this effect will have to be evaluated in a separate study where actual surgical situations are simulated. Additional algorithms, or manual correction options should be able to compensate this effect in case it has a large negative effect on the performance.

Omitting irregularities The recorded user input will have a high resolution and every move of the input device is recorded. To make sure that the acquired input shape remains a clean and simple shape it is necessary to remove loops and other intersecting lines. Smoothing of the line is another method of simplifying the shape. This does not have a significant effect on the output since the spots that are used will have a fixed spot width that won't be able to produce extreme details anyway.

Transforming into gridded data The calculations which are done to find the optimal light field make use of matrix calculations to map the individual light spots onto the target light field. This means that the simplified input shape must be converted into an image file with a resolution that is equal to the size of the target light field matrix. The individual LED spots are positioned during the mapping calculations. The step size in x and y direction will be larger if a very coarse grid is used compared to a fine grid. This is of course an advantage, but it will also slow down calculation speed.

Softening edge A single LED projects a light field with a Gaussian edge shape. This means that the edge of the combined light field can not have a shape edge that is sharper than the edge of the used LEDs. The light fields of the LEDs will be positioned along the edges during the mapping process. If an input image is used that has an edge that is much sharper than the edge of the LED, a positive error occurs on the outside of the shape edge and a negative error on the inside. The location of the spot is determined by minimizing the sum of these errors. Although this process works fine, it gives the impression of a bad match because the error image shows values near the border. Giving the target light field an edge that is close to the edge of the spot, will produce a cleaner and more feasible error image.

8.2 System dynamics

The luminaire will have to modify the strips in such a way that all the LEDs are pointed towards the optimal location to create a matching light field.

8.2.1 System state settings

The system is controlled by modifying a set of variables. Each strip has a endpoint distance that determines the curvature of the strip. The other strip variable is the angle which determines the direction in which the strips projects its light field. Next to these two strip variables has each of the LEDs that is connected to the strip a power value. The total number of variable is

$$variables = stripNb * LEDNb + 2 * stripNb \tag{4}$$

The system state variables determine the position and direction of each LED. From this it is possible to determine where the centre of each spot is on the light field. As can be seen in figure 13

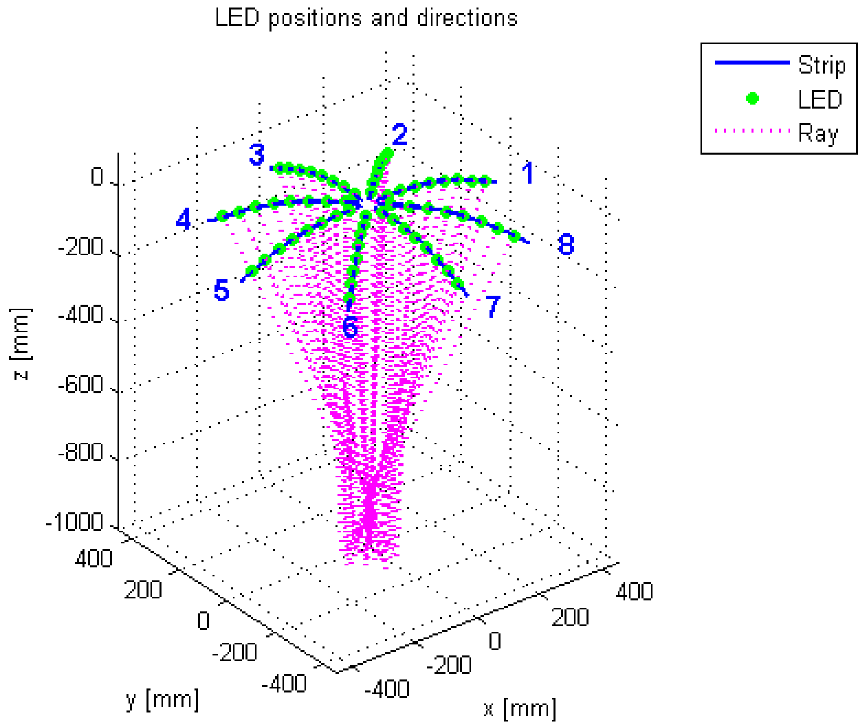


Figure 13: Example of a system state that creates a narrow beam.

8.3 Optimization process

The main goal of the optimisation is to calculate the system state settings that will produce a light field which resembles the target light field as close as possible. There are two distinct goals of the optimisation. The first is to move the focus points of the spots to a desirable location. The second is to modify the intensity of the spots. There is a strong relationship between these two parameters. If two bright spots are close to each other then it is necessary to lower the intensities to avoid a local peak error, but moving the spots away from each other can have the same effect.

The optimization process is executed in several phases. This is done because the system has many different variables and simply calculating everything in one run will take more time than needed.

8.3.1 Algorithms

Choosing the right optimisation algorithm is important for a successful optimisation process. The system with this many variables creates many local minima. The algorithm must be able to extend the search away from these points. Another aspect that is important is the time it takes to come to a solution. A badly programmed optimisation with so many variables can take very long to come to a solution, which will make it difficult to find good settings.
Another challenge is to cope with the implementation of the input images. During the optimisation process the curvature, and angle of a strip is calculated. These values can be calculated with a heigh precision. The position of the individual light spots are a result from these high precision values, but then they need to be mapped onto the light field with the fixed resolution. This means that for very small changes in the curvature and angle of a strip, the position of a light spot remains unchanged. This effect makes it impossible to find a solution for algorithms that are only suitable for functions that can be differentiated. This does not apply for the calculation of the LED power since these values do not affect spot location. That means that it is possible to carry out a power optimisation using a differentiable algorithm separately from spot location optimisations.
Using an algorithm that makes use of boundaries is beneficial because it is able to keep control over the optimisation process. This will rule out infeasible values and speed up the process.

Fmincon It is fairly fast and easy to operate. The boundaries provide good control over the values. It is not good to determine the spot locations due to the effect of resolution steps. It is very likely to end in a local minimum so it should not be used as a final optimisation for this kind of system.

Simulated annealing The algorithm is slower than Fmincon, but it is able to escape from a local minimum. To minimize the calculation time it is important to have input values that already producing a good image. It is also able to optimize the spot locations by modifying the curvature and endpoint distances.

8.3.2 Objective function

The objective function basically compares the input image with the created light field and gives a value for the difference between the two. This is done by subtracting the two matrices and summing the absolute values.

$$Error = sum(abs(inputlightfield - calculatedlightfield)) \tag{5}$$

This is a very functional way of getting a proper image. For complex shapes it might be necessary to influence the outcome to a certain degree. An example of such a situation is when a certain input shape creates an area where a large error occurs because the border of the input image is more complex than the system can produce. It is needed to tell the system to reduce the error inside the light field and except the error on the outside. This can be done by creating a penalty matrix for the inside of the light field that multiplies the error values in that area by a certain factor. Another simple example of modifying the resulting light field is to add a penalty for the height of the maximum and minimum error values. This is done when there are unwanted high intensity peaks inside the light field. The system will then give priority to reducing these peaks over accurately reproducing the shape's edge. This penalty for high peaks is used during the optimisation procedure as it is beneficial in most situations.

8.3.3 Fixed system values

A number of system values need to be determined before the calculations of the optimisation can begin. These values are kept constant throughout the analysis. The following items give an overview of the most important settings.

Strip dimensions The length of a strip is set to 400 mm. This will make the final dimension of the luminaire about 1 meter in diameter, which includes additional constructional parts. The width and thickness of the strip does not have to be determined at this moment since it is not a factor in the deformations.

Strip position The strips are place in a radial alignment with one end close to the system origin and the other outwards. The distance from the proximal end of the strip and system origin is set to 20 mm. This should give enough room to a hinge point in the construction. The angle between two strips is determined by the strip number. The angle is equal for all strips.

LED position The positions of the LEDs on the strip is determined by the number of LEDs and the way they are divided over the strip. An LED can not be placed right at the end of the strip, so a distance from the hinge to the first LED is set at 25 mm on both ends of the strip. During this analysis only a linear distribution is used, but it is possible to use other positions as well. This way it is possible to locate more spots near the edges of the shape if that would be beneficial. The position of the LEDs on the strip is a fixed value, so it is not possible to modify this dynamically.

Light field distance The luminaire is placed at a distance of 1 meter directly above the target light field. This distance is measured from the centre of the luminaire. This value will not be modified during the analysis. The luminaire will also maintain its horizontal position.

User input The user input comes in the form of a 2 dimensional image. A set of different shapes has been chosen to test the system. At later stages in the development, these images will be replaced by a real time input image that is generated by the input device. This is however out of scope for this project. Furthermore the desired luminance is declared that will determine the required lux of the inner part of the target light field. The input image is a black and white image. The sharp edged shape is transformed into an image with softened edges. The filter settings like drop box size and sigma will be declared along with the input image. The input image has a size of 1001 by 1001 pixels. The used filter settings for these images is a drop box size of 60 pixels with a sigma of 15. This creates edges that softened, but not to a degree that the contour shape of the edge is lost.

Optimisation function variables Each optimisation algorithm has specific settings that determine how the algorithm behaves. These settings include the minimum changes before the algorithm stops, the maximum function evaluations. The simulated annealing optimisation also requires a temperature that will determine the chance that the algorithm excepts a not optimal solution. This is important to escape a local minimum. Because the system is fairly complex and there are many variables is it difficult to estimate the effect of the temperature on the optimisation results. A preliminary optimisation has been done to determine what a good temperature would be for this system. The runs were done with challenging settings that will also be encountered during the following optimisations. Figure 14 shows the effect of the temperature on the results. A temperature of 0.04 gives good results although an occasional outlier is still possible. Runs at other settings showed similar results, so 0.04 is used during the optimisation process.

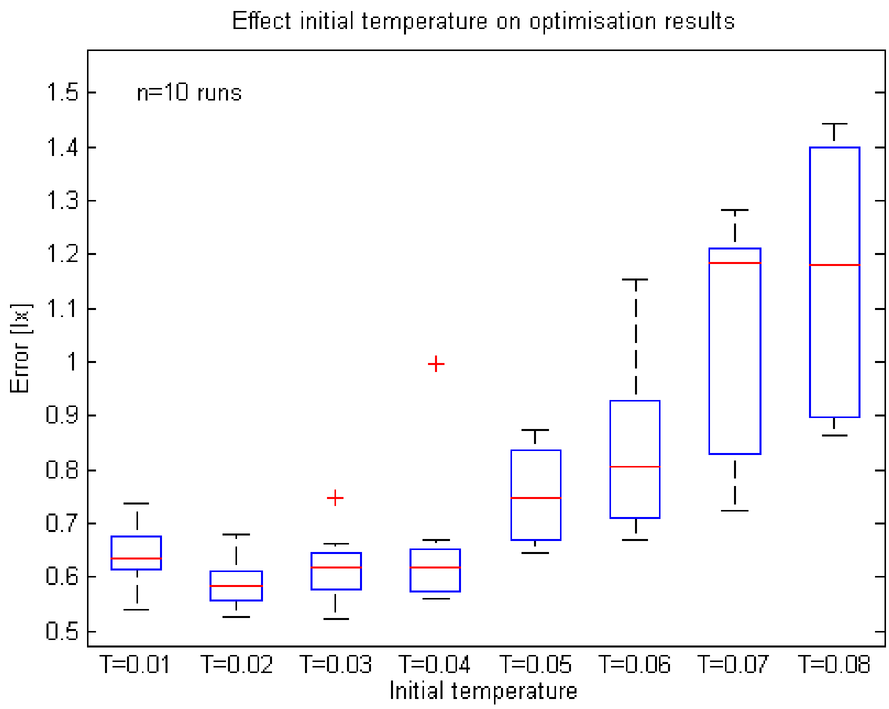


Figure 14: Optimisation results at different temperatures

8.4 Pre-optimisation calculations

Several calculations need to be done before the optimisation can be started. These calculations can be required to come to good system input values, or they can speed up the optimisation process. The following section gives an overview of the main pre optimisation calculations. Several of these pre calculations are discussed in more detail further on in this report when more required data is clear.

8.4.1 Curve height

The curve height of the strip is determined by the end point distance of the strip. As the end points move closer together, the mid point of the strip moves upwards. The relationship between these values is not linear. When the strip is flat, a certain increase in curve height causes a very small change in the end point distance, but when the strip is already curved, then the same increase will cause a much larger change in end point distance. A script was written that calculates the curve height for a range common end point distances. A model was fitted on this data to have a function that can perform the calculations quickly. This fitted model is used in the actual optimisation.

8.4.2 Shape edges

The input image has a shape somewhere inside square surface area. To assist the optimisation algorithm in finding the proper results, it is beneficial to provide good starting points. Each strip has an line over which it can position the LEDs. This line intersects the input shape. A Matlab function was written that calculates for each strip the points where the line crosses the edge of the shape. These points points help the system determine proper boundaries and start values. The output of the function determines at which angle and curve height the outer LEDs are placed on the edges of the shape.

8.4.3 Spot shape

The shape and size of the spot is an important factor in the ability of the system to create a proper fitting light field. For the final system a LED and lens combination will be chosen. This determines the main properties like the peak power and the full width half maximum value. These will be needed to create a small image that represents the spot. This image will be used in the optimisation process. The size of the image is determined as $2 * FWHM$ This is wide enough to include the smooth transition. The smooth Gaussian shape extends beyond this region, which creates a small threshold at the edge of the defined spot area. The maximum threshold value is subtracted from the spot, the negative values are set to zero and the drop in peak power that the subtraction causes is corrected. The result is a smooth and circular Gaussian, as in figure 4.

8.4.4 System boundaries

System boundaries are needed to keep the algorithm focussed on calculating feasible results. These boundaries are based on physical limitations of the system. The LEDs can provide a certain amount of light. This results in a boundary for the power which is between 0 and 1.

The curvature of the strip has a limitation in that when the strip is flat, the maximum endpoint distance is achieved. In this research a strip of 400 mm is used. It is also good to provide a lower limit to the end point distance. The strip must be able to create a width that can span the image, but curving to far will cause problems with plastic deformations of the strip. A lower limit of 380 mm is used. This corresponds to a curve height of 57 mm.

The angle of the strip is adjusted by lowering the distal end of the strip. The amount of possible displacement is limited in that the range of motion will become very large for actuators to accomplish. Another reason to limit the angle is that getting an angle that is so large that the light field moves off the target light field is useless. The strip angle is set to be between that -0.25 rad and 0 rad. This gives an maximum angle of around 15 deg. It allows room to place the strip light field properly inside the combined light field.

8.4.5 system start values

The optimisation algorithm requires start values for each of the system variables. These values influence the outcome of the process, so it is important to choose them properly. The outcome of the previously discussed function that calculates the shape edges is a very good starting point for the angle and curve height. These values provide an optimal spread of spots along the surface area of the target light field. It is a little less easy to find good starting points for the LEDs. The simulated annealing algorithm takes quite long to find proper values when they start at a point that is fairly far away from the final optimum. Luckily it is possible to use the fmincon function on the power of the LEDs, which is much faster in getting to a feasible result. Because the fmincon function will likely get stuck in a local minimum, is it necessary to perform a second optimisation round on the power values using simulated annealing. This means that there are two optimisation rounds. The first calculates the power values. The angle and curve height are fixed at the position that was calculated by the image mapping function. These power values are used as inputs for the second optimisation round. This time also the angles and curve heights are recalculated in a simulated annealing process.

9 Design analysis

Multiple design choices need to be made to come to a properly functioning luminaire system. A thorough examination of the different options is needed to be able to tell the effect they have on the way the device will function. Each design option will be examined individually if possible. The following choices will be examined.

- Strip number
- LED number
- LED power
- Spot size
- LED strip positions

For each setting an optimisation procedure is carried out. This produces light field data that will be analysed to determine the effect of each setting. Several types of graphs will be used to show these effects. Figure 15 and 16 show the generated light field. The Z-axis can be normalized like in figure 15, or it can show the actual luminous intensity like in figure 16. For the normalized representation the generated intensity values have been divided by the target luminous intensity. This makes it easier to compare settings with different target intensities.

The black line inside the graph shows the outline of the target light field which helps to judge how well the generated light field matches target light field. A text box inside the graph shows several settings that were used to generate the light field.

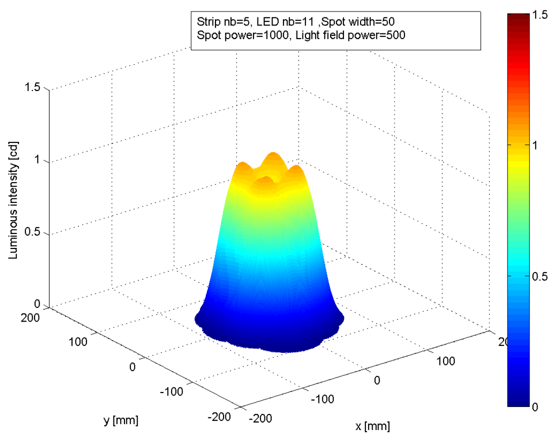


Figure 15: Error field isometric

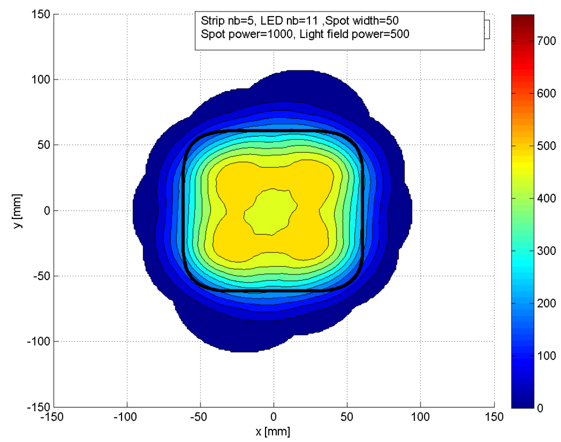


Figure 16: Error field contour

Figure 17 shows the error between the generated light field and the target light field. This figure can be represented normalized or regular, like the figures for the generated light field. In the optimal case this figure would be empty except for the outline of the target light field. A text box shows the largest positive error value, the largest negative error value and a total error value. The total error value is the summation of the error field, divided by the number of pixels. Figure 18 shows the positions of the individual spots inside the light field. A blue dot is the centre point of a spot. The green lines connect the spot locations that are projected by LEDs which are attached to the same strip. The number next to a green line shows the specific strip number. The text box inside the graph gives the average power of all the LEDs.

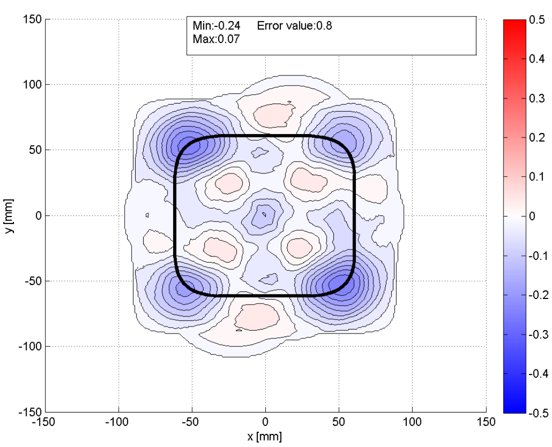


Figure 17: Error field

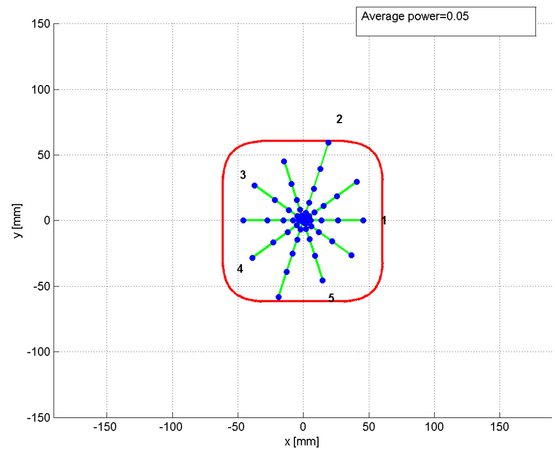


Figure 18: Spot locations

Whether or not a setting or result is feasible is not of major interest at this point of the analysis. The main goal is to analyse the effects of certain settings. The power of the used LEDs, for example, is often unrealistically high. This way errors cause by other effects than lack of power become better visible. At a later stage of the design process an analysis will be made to see what the limits of a realistic system will be.

After examining the effect of the previously listed design choices, an analysis will be done to determine the effect of several input factors on the system's performance. The following factors will be examined.

- Target light field shape
- Target light field size
- Target light field rotation
- Target light field position

9.1 Design variables

9.1.1 Strip number

The number of used strips is a primary factor in the resulting light field. Each strip is only capable of placing its spots close together, or creating an elongated light field. The orientation of this light field inside the combined light field depends on the radial alignment of the strip. Assuming that equal angles are used between the strips, then it makes sense to use an uneven number of strips. An even number of strips would have the negative effect that the axis over which two opposite strips can position their light field would coincide. This reduces the number of axis that cross the target light field by a factor 2, as can be seen in figure 19 where using 6 strips gives the same number of axis as when using 3 strips. The higher the number of axis, the better the luminaire is able to spread the light over the target light field. The effect that an added strip has on the performance reduces as more and more strips are used as can be seen in figure20. The blue line shows the resulting error value when an uneven number of strip is used and the red line when an even number is used. As expected is the performance with an uneven number of strips much better. The blue line is no longer decreasing when more than 7 strips are used. These error values are generated using the same setting and target field, with only the strip number varying. The complexity of the target light field and the diameter of the LEDs will also influence these results. This means that it might be beneficial in other situations to use more than 7 strips. On the other hand, using a high number of strips increases the complexity of the system. Another limit to the number of used strips that can be used is the space it takes inside the luminaire. For most following settings a strip number of 7 is used.

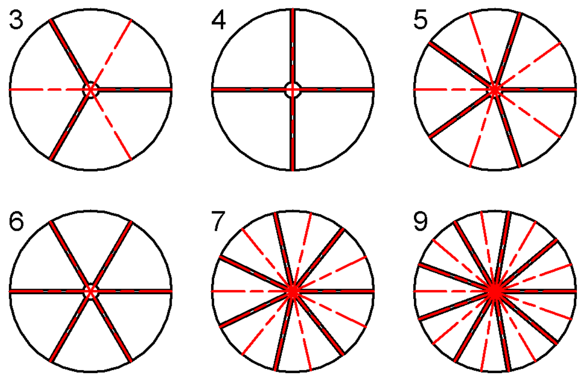


Figure 19: Effect of strip number on illumination axis

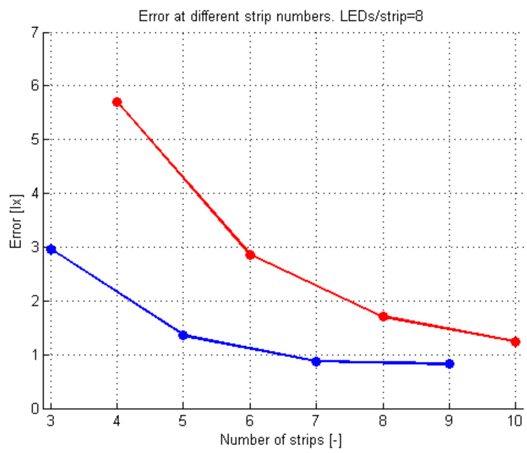


Figure 20: Effect of strip number on illumination axis

9.1.2 LED number

The number of LEDs on a strip has influence on the total maximum luminary output of the system and also in the distance between the individual spots inside the combined light field that is projected by a single strip. Increasing the number of LEDs will benefit the abilities of the system. The number of LEDs is limited by the space that each LED requires on the strip. There are several consequences of increasing the number of LEDs that have a negative influence on the functioning of the luminaire. It increases the computational effort that is needed to calculate the optimal light field, which might result in a slow responding system. It increases the power consumption, which will require more

electrical components and produces more heat. Another factor is the increase in mechanical load of each strip. This influences the deformation of the strip.
Figure 21 shows the effect of the number of LEDs on the error value. The system consists of 7 strips and the required light field intensity is 500 lux. The light fields have been calculated at three different LED power settings because the number of LEDs has a strong effect on the total luminary output and therefore also on the error value. As expected is there a clear decline in error value as the number of LEDs on a strip increases. It is clear that the error value is relatively high when using only 4 or 5 LEDs on a strip. Using more LEDs improves the performance drastically. The difference between using 6, 7 or 9 LEDs is not so large. The system is able to provide the needed amount of coverage at these numbers. The increase in error using 9 LEDs is probably caused by a local minimum during optimisation.
Figure 22 shows the average control power. As the LED number increases the average power decreases, which behaves as expected.
It can be concluded that using to few LEDs has a negative effect on the systems performance. At a certain number of LEDs the effect the error value becomes less obvious. It does however have a strong effect on the average control power, so when a high light field intensity is needed, a large number of LEDs is required to be able to generate a proper light field.

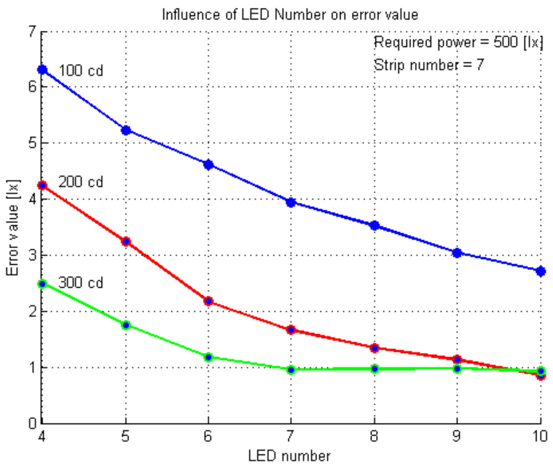


Figure 21: Effect of strip number on error

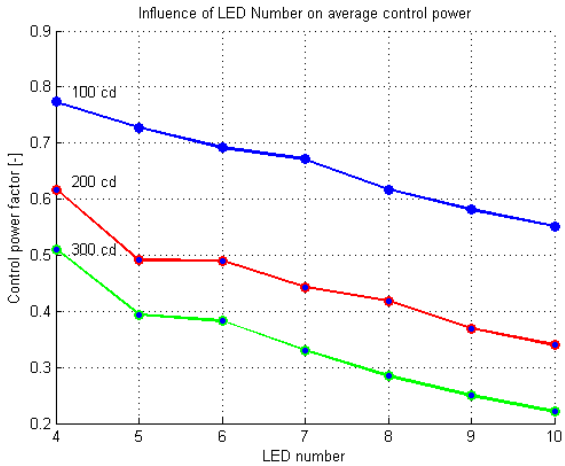


Figure 22: Effect of LED number on power

9.1.3 LED power

The user input consists of a shape and a target intensity. Whether the system is able to achieve this target intensity largely depends on the power of the LEDs. The available power is still one of the main challenges during development of this system, although LEDs are becoming more and more powerful. The way the system functions is different from current multi LED systems in that, with an adaptable light field, not all LEDs point at the same spot. This means that a single LED will have to provide a bigger contribution to the illumination of a certain part of the combined light field. A light field has been generated at a range of different LED peak powers to analyse what illumination levels can be expected of the system.
The target light field is set at a value of 500 lux. Figure 23 to 30 show the produced light and error fields. At low power levels of 50 and 100 lux the system is clearly unable to fill the fairly large target

light field. The required levels are only reached in the centre of the light field where many spots are located close together due to the crossing of the strip's illumination axis. The At 200 lux and higher the system is able to produce a much better image.

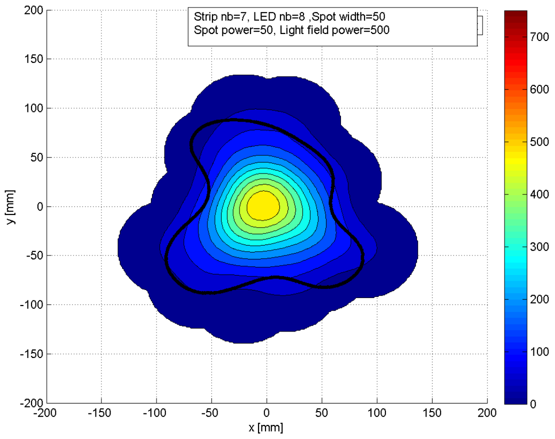


Figure 23: Power = 50

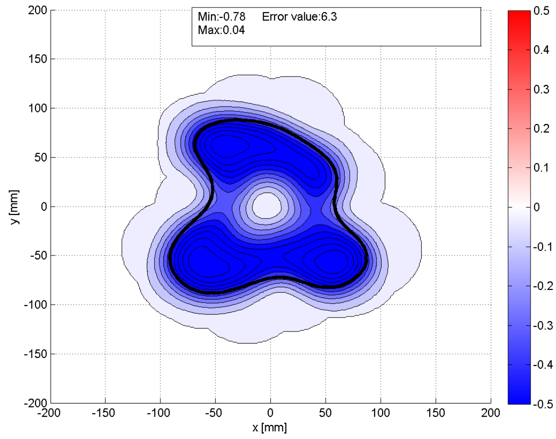


Figure 24: Power = 50

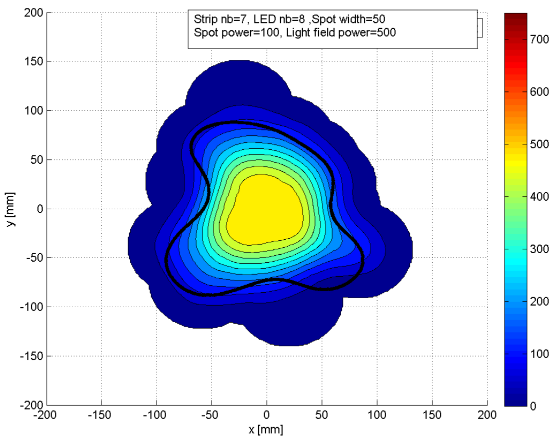


Figure 25: Light field at power=100

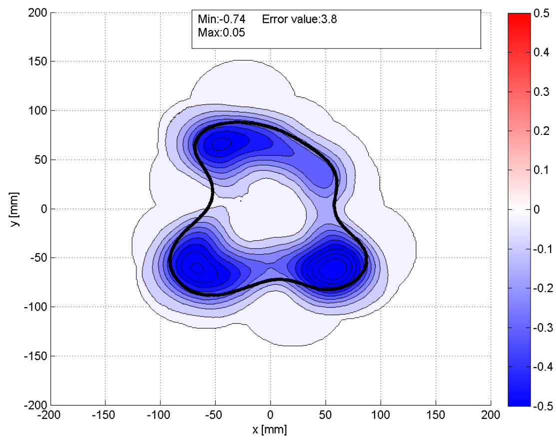


Figure 26: Error at power=100

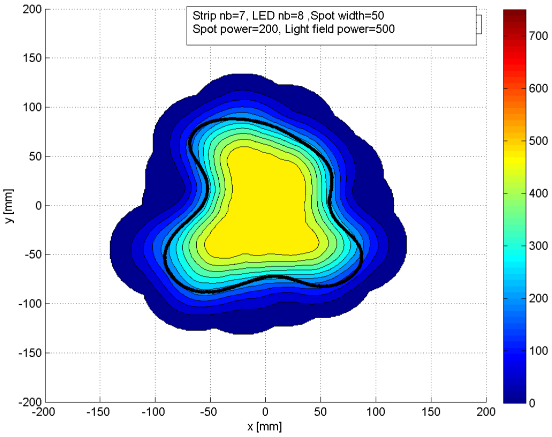


Figure 27: Light field at power=200

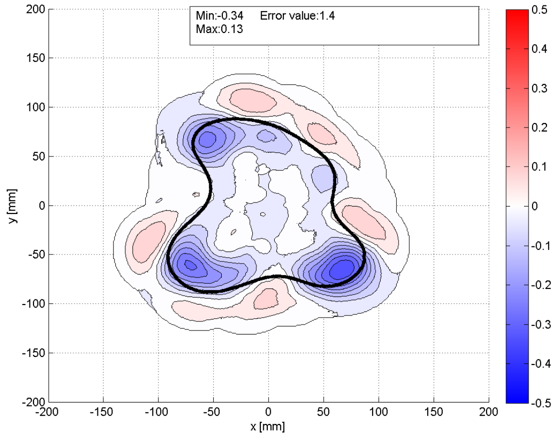


Figure 28: Error at power=200

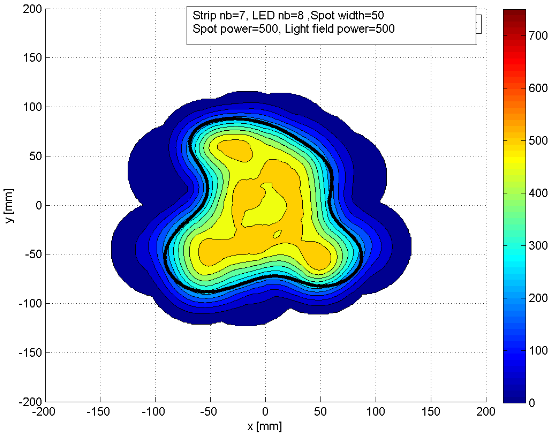


Figure 29: Light field at power=500

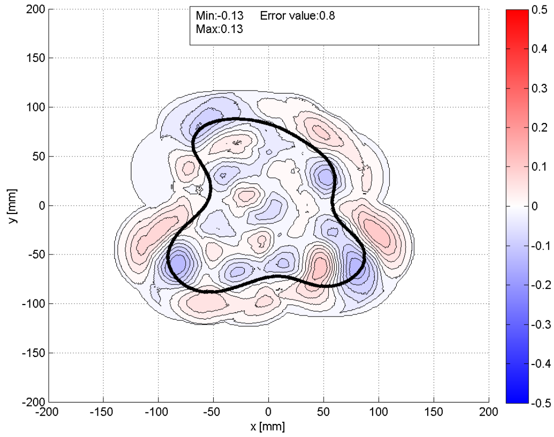


Figure 30: Error at power=500

Figure 31 gives an overview of the influence of the power on the error values. The error is very high when the LEDs are relatively weak. It decreases drastically until the peak power is about half the value of the target power of 500 lx. After that the error value is not reduced by increasing the peak power further. The average activation power decreases as the peak power increases as can be seen in figure 32. This decline is expected. The smooth decreasing slope is the result of overlapping spots in the centre of the shape. This makes that the activation power of the central LEDs are not equally affected be an increase in peak power, which smooths out these effects.

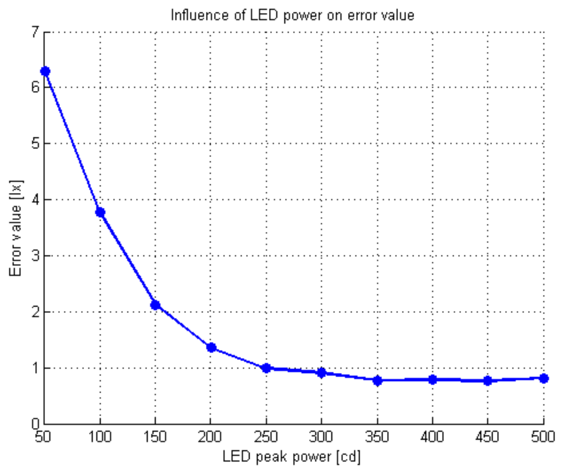


Figure 31: Error / LED power

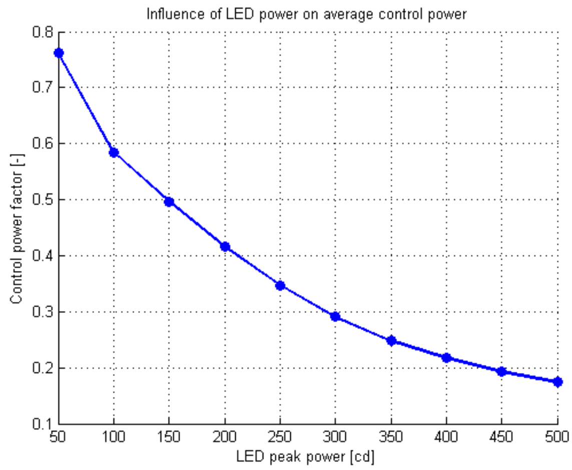


Figure 32: Average power / LED power

9.1.4 Spot size

The size of the spot that each LED produces is an important factor that determines how well the system can produce a proper light field. If the spot size is relatively large, then the luminaire will not be able to produce accurate edge details. If the spot size is relatively small, then the inner area of the light field will become fragmented because there is not enough overlap between spots.

The size of the spot depends on the divergence angle of the light beam and the surface distance. The divergence angle is a property of an LED in combination with a particular lens. The current design is based on a fixed lens, which means that the beam angle can not be modified. It is possible to make a system where the spot size can be modified dynamically, but this requires a far more complex system and should therefore only be considered if a fixed spot size proves to be impractical.

There is a clear relationship between the surface area of the target light field and the error value that a spot of a certain size produces. Larger surface areas will increase the distance between the individual spots, which reduces the overlap between spots. This overlap is needed to sustain illumination intensity throughout the total shape. A small spot will be good at generating a fitting light field for smaller shapes with detailed edges, but will be much less successful at creating a larger shape.

To test various spot sizes a light field has been generated with a range of spot sizes. The settings were done with the standard 7 strips, containing 8 LEDs. An amorph target shape was used. Figure 33 shows the resulting error values for a range of different spot sizes. The smallest was 20 mm and the largest 80 mm. It is clear that a very small spot size results in a poor performance. The error value drops rapidly when the size increases from 20 mm to about 35mm. From about 50 mm the error value starts to slowly increase again. The average power decrease as the spot width increases, which can be seen in figure 34.

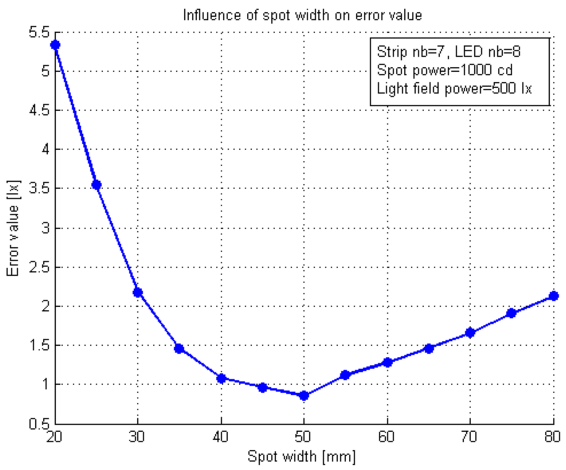


Figure 33: Effect of spot width on error value

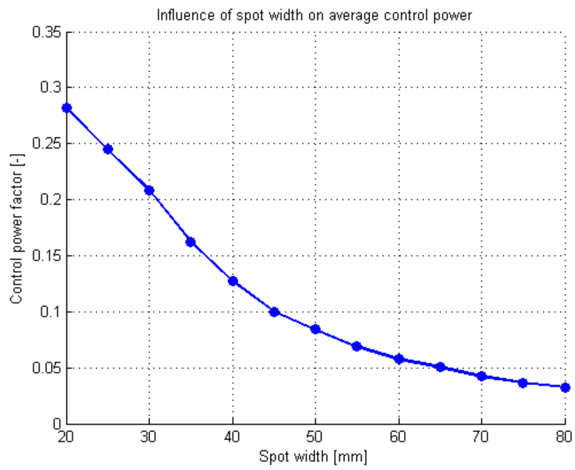


Figure 34: Effect of spot width on average power

Figure 35 to 44 show some of the generated light fields and error fields. It is clear that a spot width of 20 mm is not sufficient for a good fill of the shape. When the spot size increase the fill becomes better, until the spot size becomes fairly large. At large widths the system is unable to produce proper edge details which increases the error values. The largest setting with a width of 80 mm doesn't produce a proper light field.

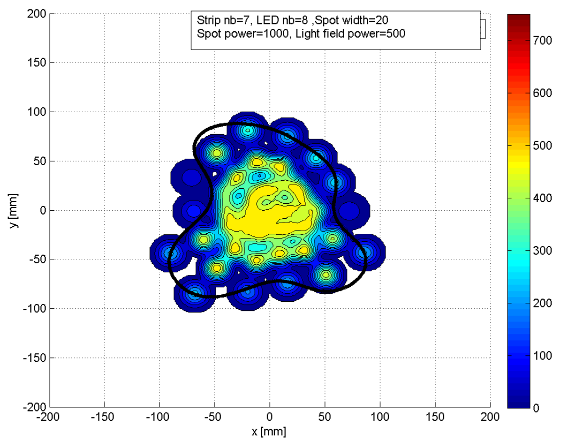


Figure 35: Light field at spot width 20 mm

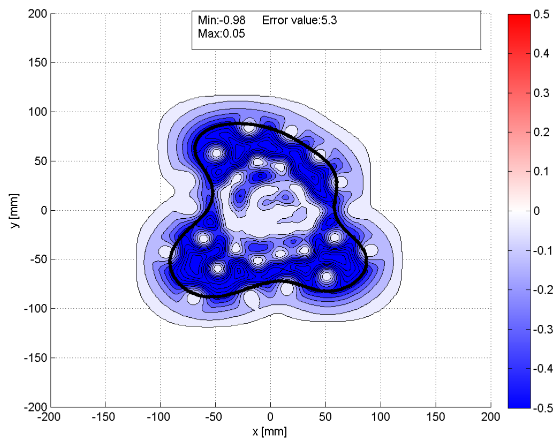


Figure 36: Error field at spot width 20 mm

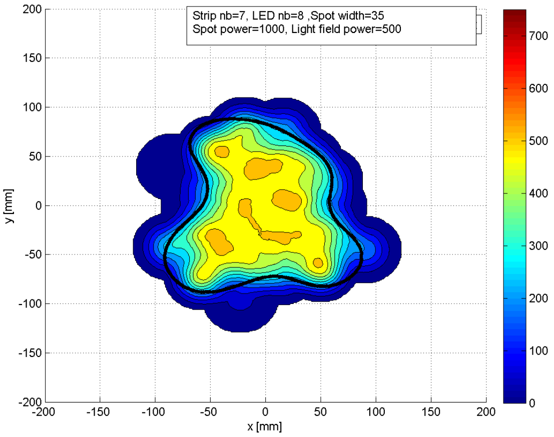


Figure 37: Light field at spot width 35 mm

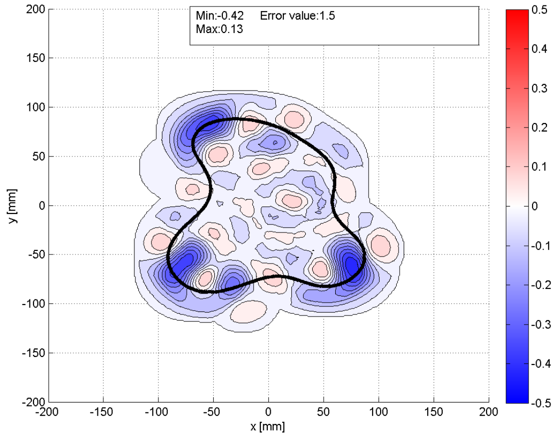


Figure 38: Error field at spot width 35 mm

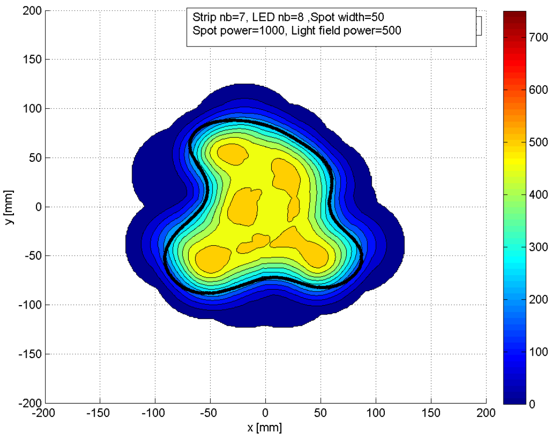


Figure 39: Light field at spot width 50 mm

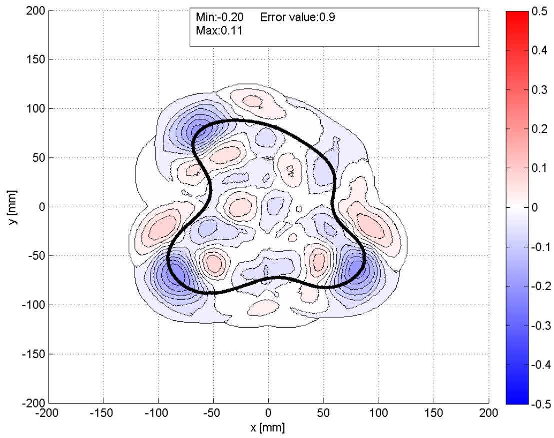


Figure 40: Error field at spot width 50 mm

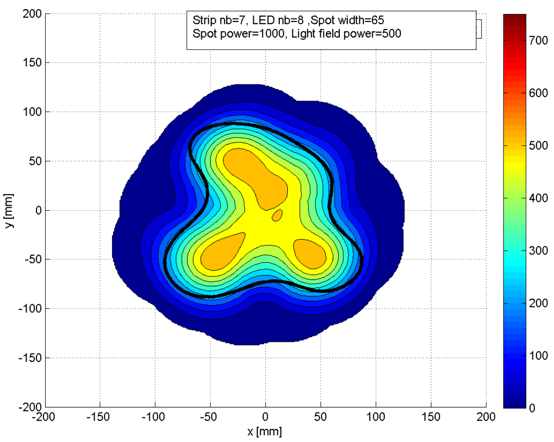


Figure 41: Light field at spot width 65 mm

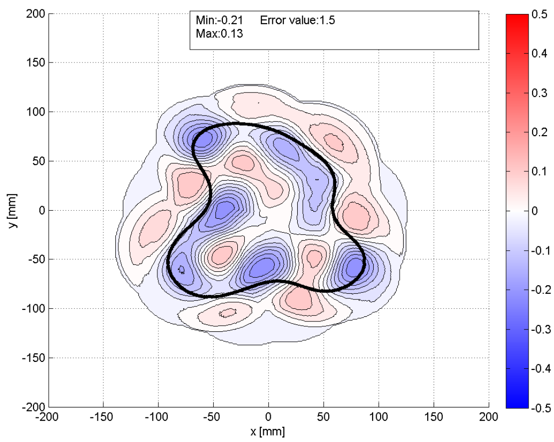


Figure 42: Error field at spot width 65 mm

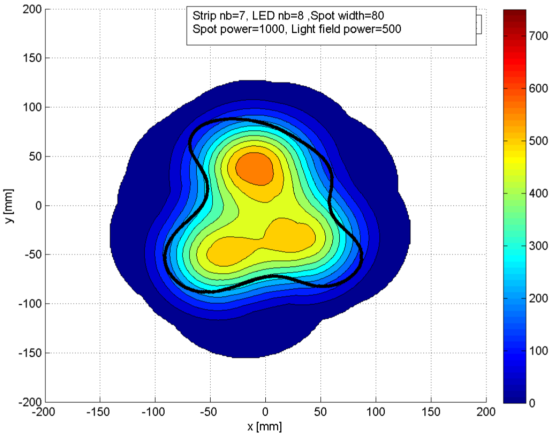


Figure 43: Light field at spot width 80 mm

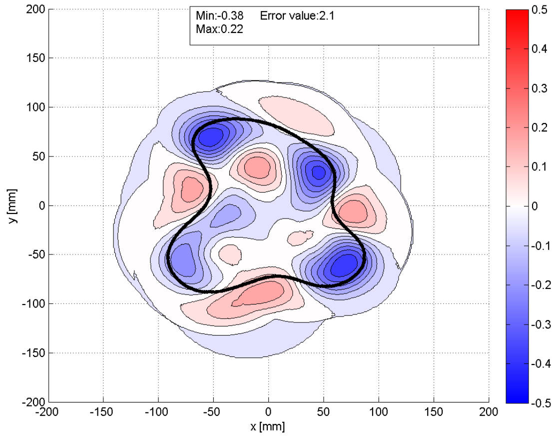


Figure 44: Error field at spot width 80 mm

Figure 45 and 46 show the locations of the spots at 50 mm and 80 mm. It shows that the system has to move the spot locations towards the centre to compensate for the large spot widths.

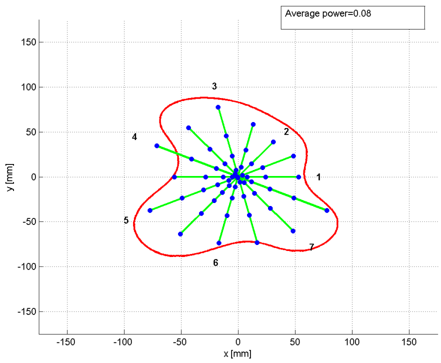


Figure 45: Effect spot size (50mm)

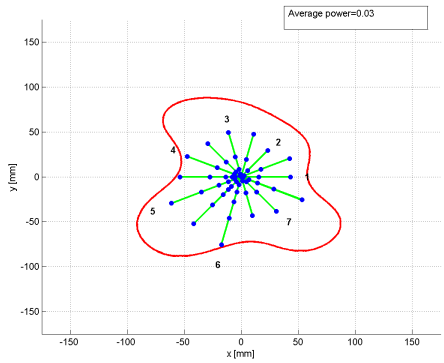


Figure 46: Effect spot size (80mm)

It can be concluded that the proper spot width is an important factor. Because it is not possible to easily change the spot width after construction is this choice crucial. The spot width must allow the production of a proper light field, also if the size of the target shape changes. A width of around 50 mm seems to be optimal.

9.2 Target variables

The target variables will give information about the conditions that will be encountered during use.

9.2.1 Target shape

The ability to project different target shapes is the main feature of the system. There are of course limits to what the system can do, but the system should be able to produce a large diversity in shapes. Figure 47 and 48 show the reproduction of an amorph light field. The system is able to cope with the lack of symmetry well enough to produce a properly fitting image.

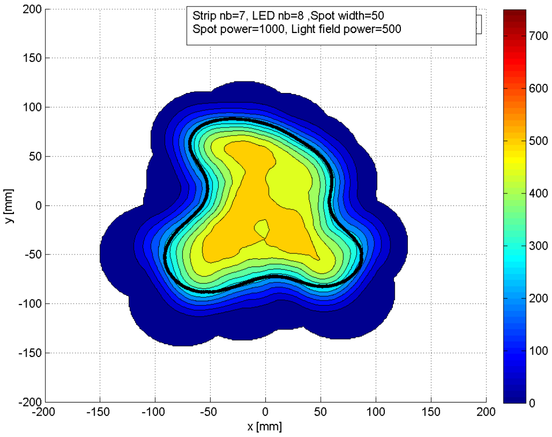


Figure 47: LF amorph shape

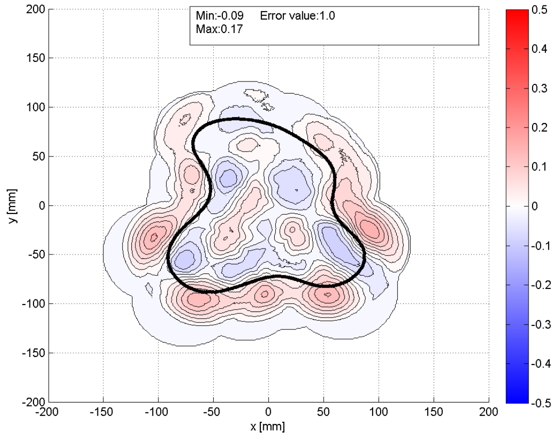


Figure 48: EF amorph shape

Figure 49 and 50 show the reproduction of an circular light field. The symmetry makes it easier to produce a proper light field, so the reproduction is quite good. Current systems are able to produce circular light fields, but they are not able to produce a light field with a flat distribution inside the shape.

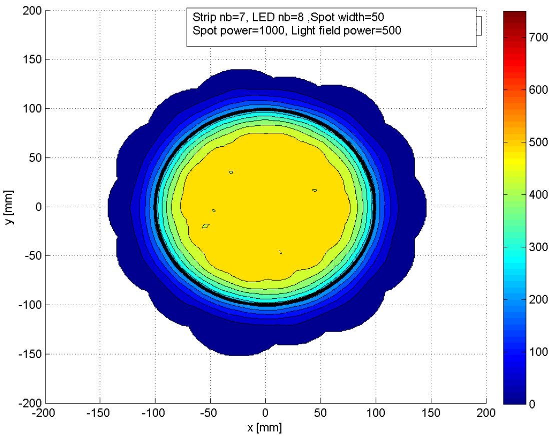


Figure 49: LF circular shape

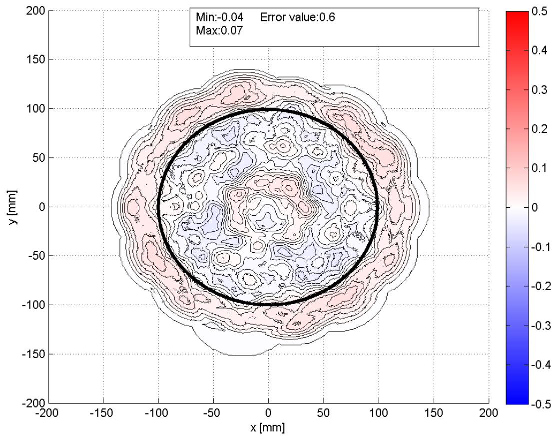


Figure 50: EF circular shape

A simple elongated light field is very likely to be encountered often during practice. The reproduction of a simple oval shape is shown in figure 51 and 52. The system is able to create the shape fairly good. The two furthest edges of the shape are the most challenging which can be seen as a slight increase in the error value at the top and bottom of the shape.

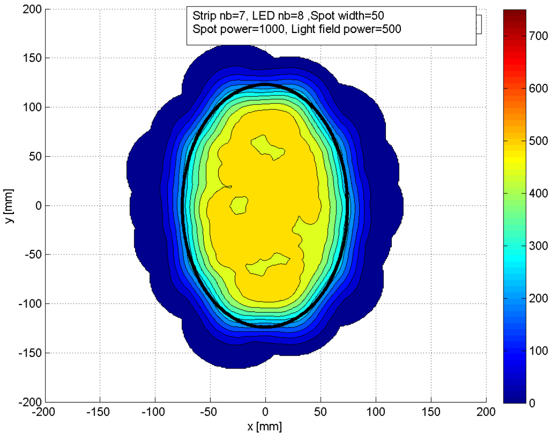


Figure 51: LF elliptical shape

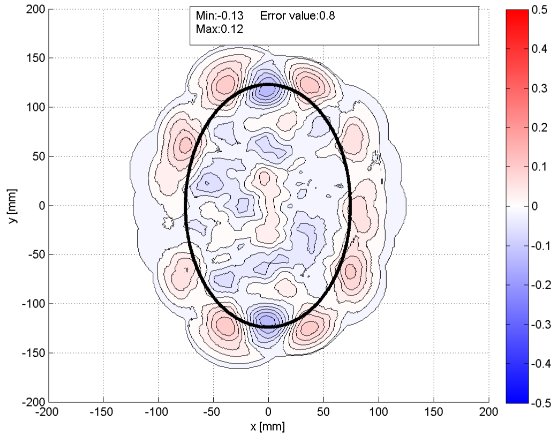


Figure 52: EF elliptical shape

A rectangular shape is also a common shape as it resembles a situation where clamps are placed in the wound area to spread the surface apart. The challenge for this shape is found in the length compared to the width. The system is able to produce a nicely fitting light field.

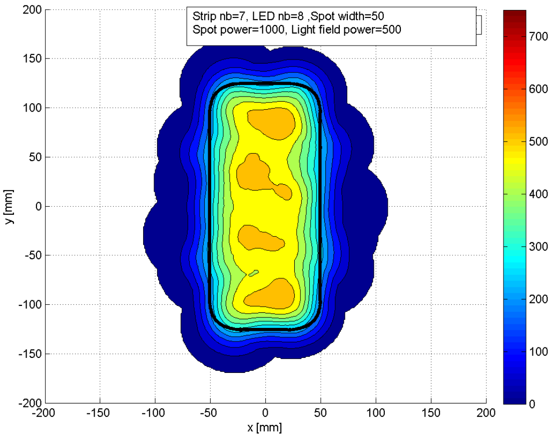


Figure 53: LF rectangular shape

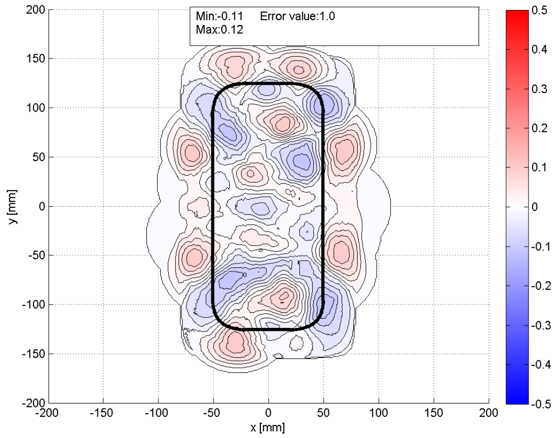


Figure 54: EF rectangular shape

An elongated shape with a curve in it like the banana shape in figure 55 and 56 is challenging because the intersection point of the strip axis falls close to the border of the shape. Also the long and narrow shape is a challenge. The result is an increase in the maximum negative error value, but still the shape is fairly consistently reproduced.

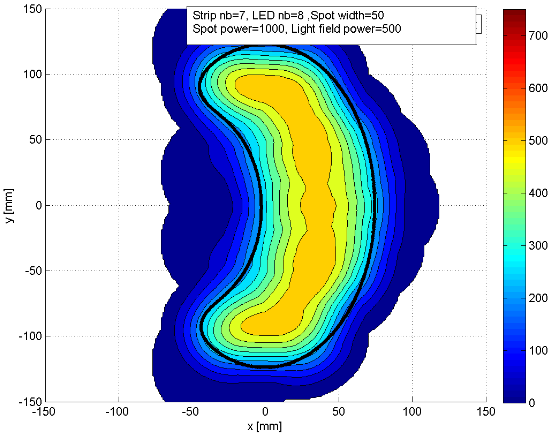


Figure 55: LF Banana shape

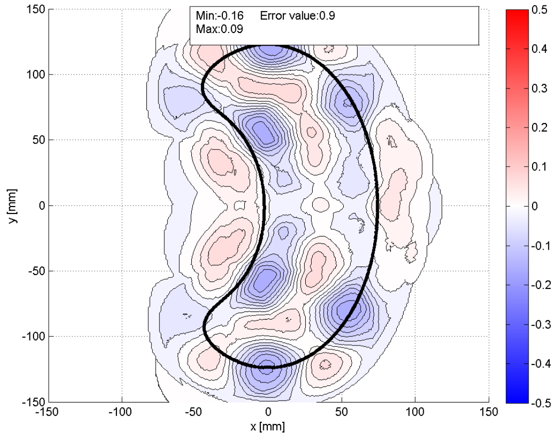


Figure 56: EF Banana shape

If there is an area inside the wound where the surgeon does not want any light, for example in the presence of a highly reflective instrument, then the surgeon can indicate that light is unwanted in that particular area. The system then has to move the spots away from that location, or it has to switch them off. The oval shape in figure 57 and 58 has a small spot inside it where no light is wanted. This is quite a challenging situation, but the system able to reduce the light inside blocked area without loosing to much light around it. There is still a small amount of light that falls on the blocked area, but the reflections should be largely reduced.

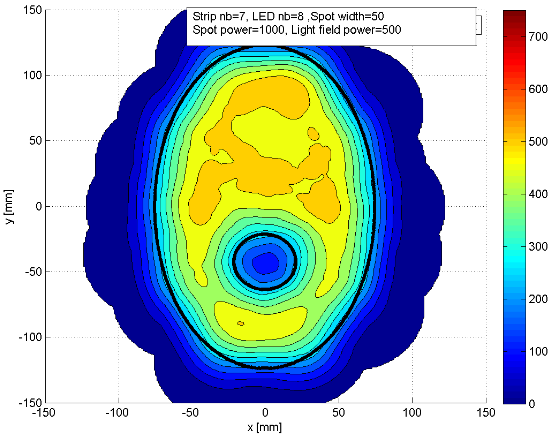


Figure 57: LF oval with small hole

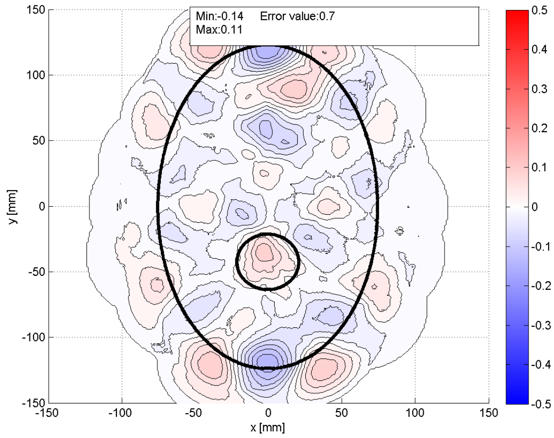


Figure 58: EF oval with small hole

Figure 59 and 60 show an oval shape with a larger hole than in the previous example. The system is now able to reduce the light inside the blocked area further, but it comes at the cost of the illumination power below and around the blocked area.

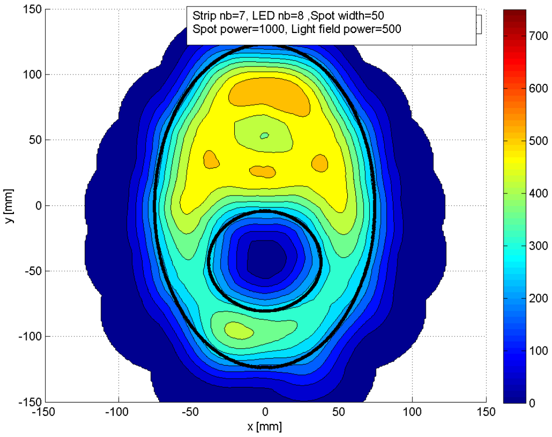


Figure 59: LF oval with large hole

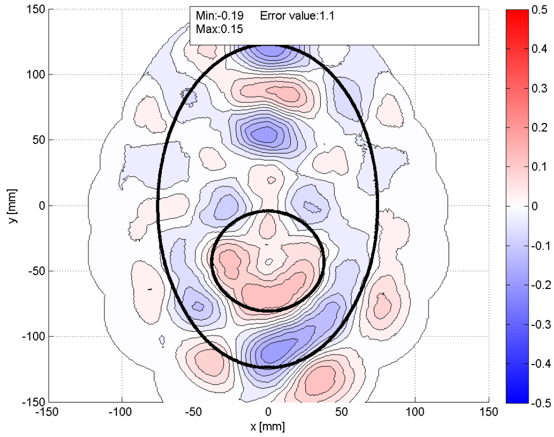
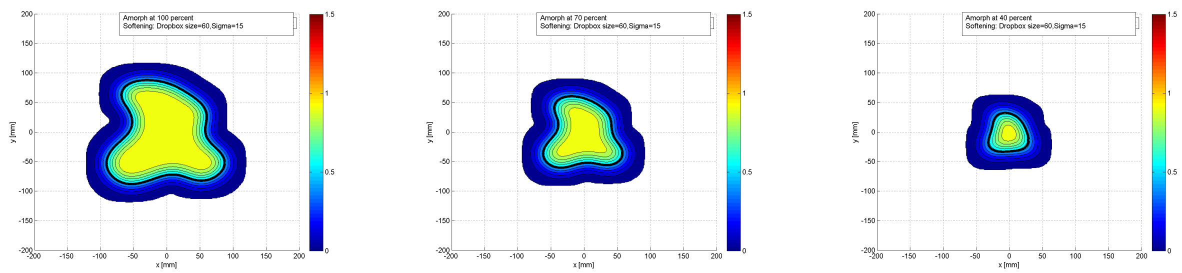


Figure 60: EF oval with large hole

9.2.2 Target size

There is a clear relation ship between the size of the target light field and size of the spots when looking at how well the system is able to produce the required light field. As could be seen in section 9.1.4, small spots will have difficulty filling a large light field and large spots will be unable to provide the required edge details. The major difference between modifying the spot size and modifying the target size is the effect that post-processing of the user input has on the target light field. A blur filter is applied to the input shape to create a feasible target light field. The effect of this is that small light fields will be effected more by the filter and loose more shape details. This effect can be seen in figure 61. This is not necessarily a negative effect, since a very detailed target light field is not a realistic target. However it does indicate that the chosen filter settings should match the shape of the spot, or else more details might be lost than needed.



(a) 100% (b) 70% (c) 40%

Figure 61: Blur filter effect

The abilities to reproduce a target light field at progressively small sizes has been analysed. As can be seen in figure 62 to 67 the system is able to maintain a proper reproduction as the size increases

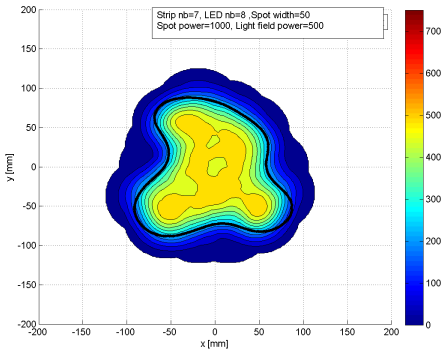


Figure 62: Light field at 100%

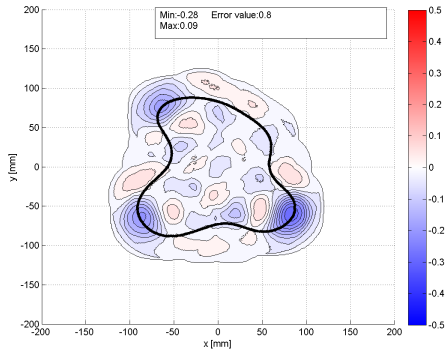


Figure 63: Error field at 100%

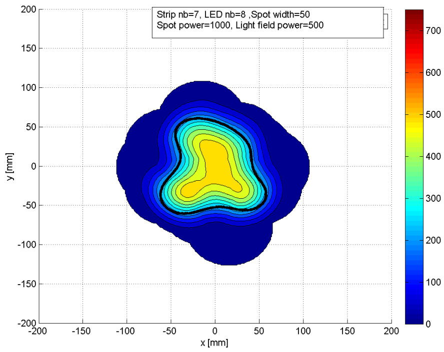


Figure 64: Light field at 70%

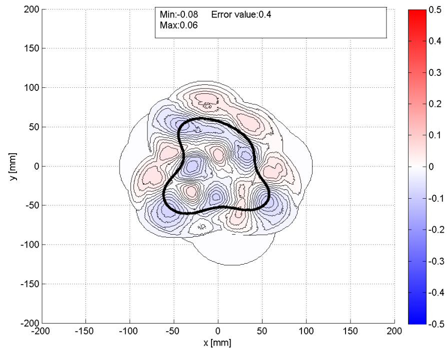


Figure 65: Error field at 70%

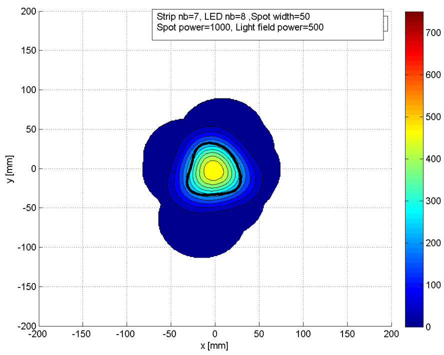


Figure 66: Light field at 40%

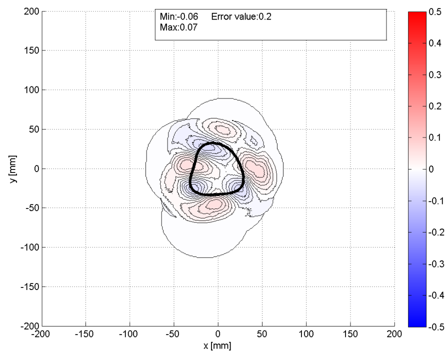


Figure 67: Error field at 40%

To be able to compare the error values with each other it is needed to compensate for the decrease in surface area of the light field. Figure 68 shows the relation ship after this correction. A slight decrease in error value can be seen as the target size increases.

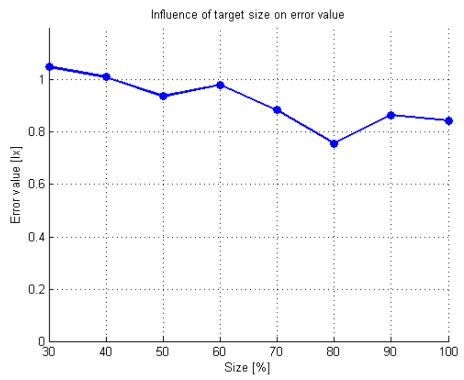


Figure 68: Effect target size on error

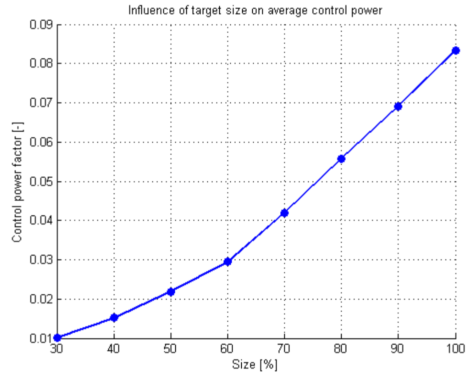
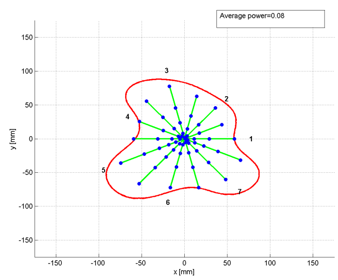
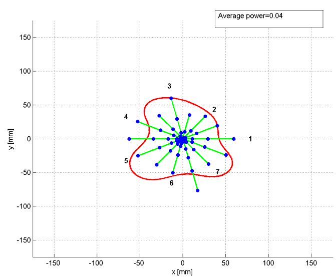


Figure 69: Effect target size on control power

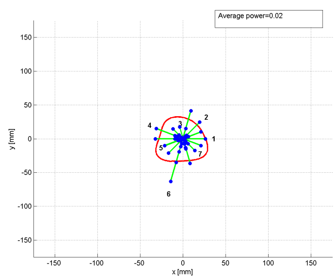
The locations of the spots will be located closer towards each other as the target light field gets smaller. This means an increase in overlap between the spots, which reduces the required output power of an LED. This can also be seen in figure 69. Light fields with this many spots close together allow some LEDs to be switched off. This can be seen in figure 70c and 70b where some LEDs are placed outside the target light field. Overall the performance of the system is not highly dependant of the target size.



(a) 100%



(b) 70%



(c) 40%

Figure 70: Blur filter effect

9.2.3 Target rotation

The number of strips determine how many axis cross the target image. When the image is rotated, the axis intersect a different part of the image. This will affect the calculated system state variables and therefore also the error value. It is assumed that the light field and luminaire remain in the same position and orientation during the surgical procedure, so rotation is not a dynamic factor that the system will have to cope with. The effect of rotation is however of interest when fluctuations in the error value are large. In that case it might be an interesting addition to enable the system to perform a small rotation if that would improve the system's abilities. The maximum needed rotation would in that case be $360/(2 * stripnumber)$ The system is run with a square input image at several rotation steps. The strip number is 7, so at 25.7 degrees the area between two strip axis would be covered. The results for the error values can be seen in figure 71. It is clear that there is very little effect on the error values. The spread is probably close to the fluctuations in the optimisation process. This indicates that it is probably not needed to incorporate the ability to change the rotation of the system when a strip number of 7 or higher is used. The largest difference can be seen at a rotation of 0 and

20 degrees. The difference between these two light fields is very small as van be seen in figure 72 and 73. The error fields in figure 75 and 75 show similar results. The difference in average control power between the runs was negligible.

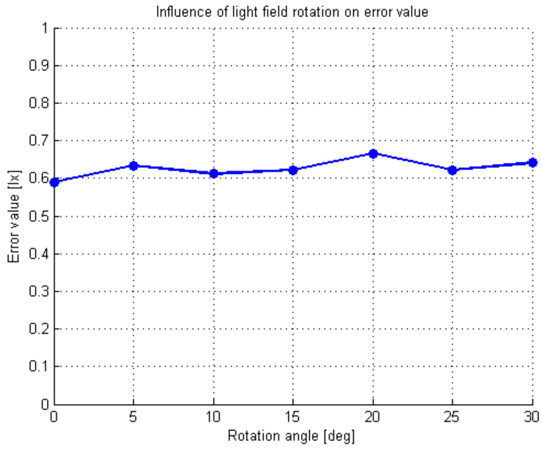


Figure 71: Effect of rotation on error value

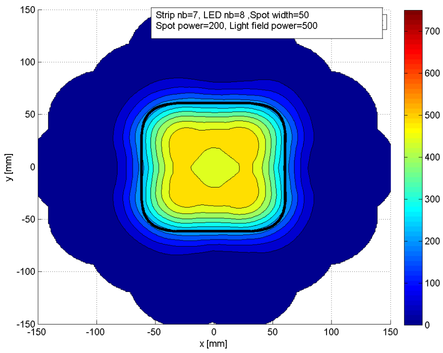


Figure 72: Rotation = 0 deg

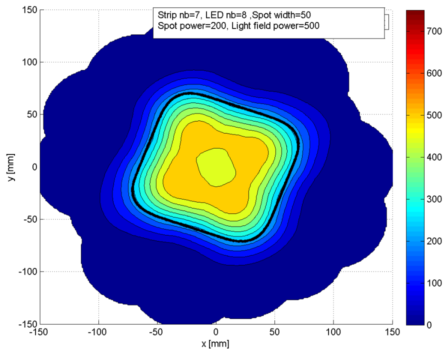


Figure 73: Rotation = 20 deg

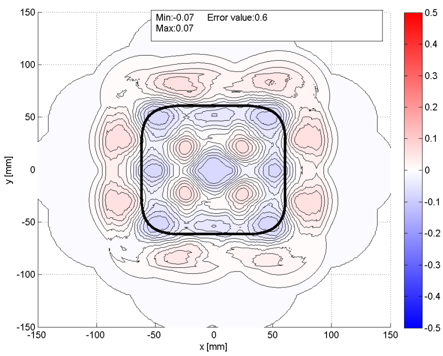


Figure 74: Rotation = 0 deg

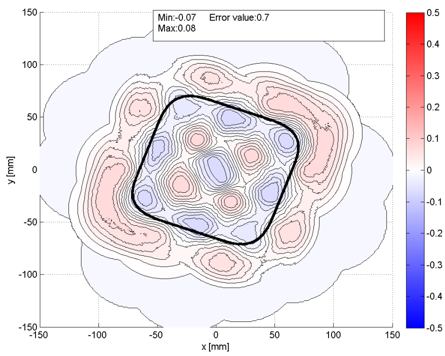


Figure 75: Rotation = 20 deg

The algorithm has calculated the optimal locations of the spots to be widely spread over the image as can be seen in figure 76 and 77. The outer LEDs are not used to create the light fields. The strips are properly adjusted to compensate the change in orientation. Given the good results and logical adaptations it can be assumed that these result are indeed close to optimal.

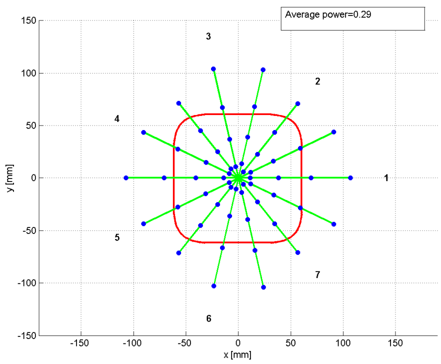


Figure 76: Rotation = 0 deg

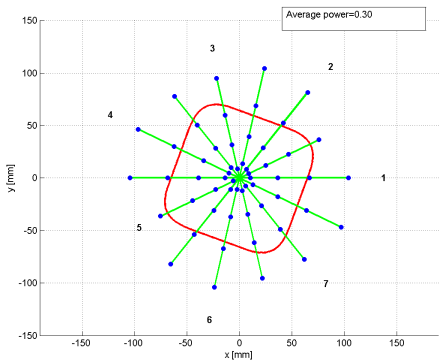


Figure 77: Rotation = 20 deg

9.2.4 Target position

The position of the target light field in relation with the location and orientation of the luminaire is very important for the functioning of the device. The intersection point of the strips is positioned directly beneath the luminaire. The position of this intersection point inside the target light field determines where the strip axis cross the light field. The system will try to compensate a faulty placement of this point by increase the strip angles. This will only work for the strips that are oriented in such a way that changing their angle allows movement in the required direction. Strips that are in a more perpendicular orientation will not able to relocate their light fields properly. The possibilities of the system to adapt to this situation is limited by the minimum curvature and the maximum strip angles. Figure 79 shows how the system is trying to compensate for a misalignment. In this fairly extreme situation is the intersection point located outside the target light field. The strips which are able to compensate will reduce the strip curvature to create a larger spread and they will increase the angle to shift their light field to the left. This way the spots are still able to reach a large part of the target light field. Strip number 3 is in this case not able to move its light field inside the target shape. Therefore the LEDs on this strip will not participate in creating this light field.

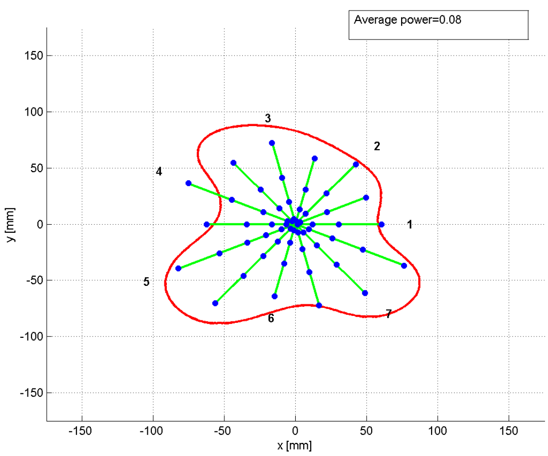


Figure 78: LED positions at 0 mm 80 mm

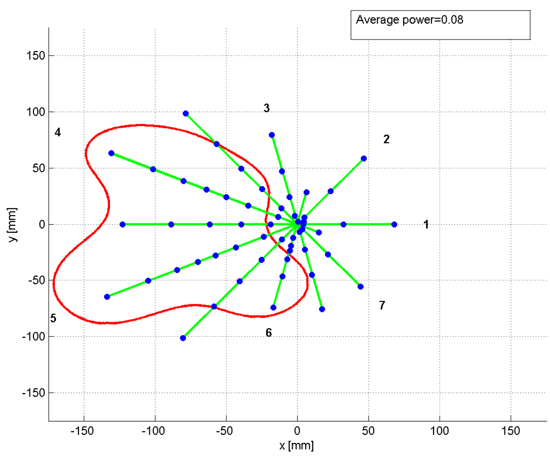


Figure 79: LED positions at 80 mm

the effect on the shape of the light field and the error field can be seen in figure 80 to 87. The left side of the light field is where the problems start to form. The reduction in the number of crossing axis and thereby a lower spot density has an expectable effect on the error field. The areas in between the spots can no longer be illuminated properly. The right hand side of the image remains properly illuminated and is not affected by the misalignment.

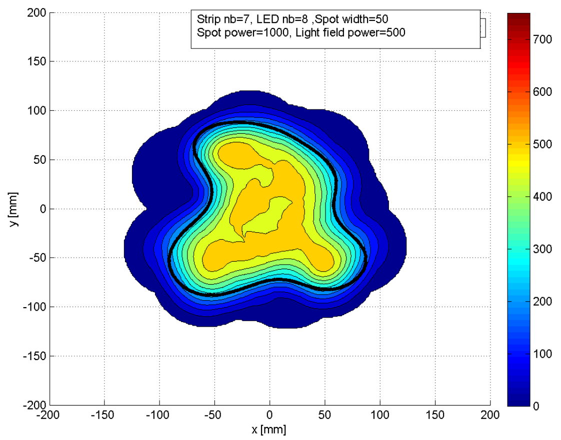


Figure 80: Light field shift 0 mm

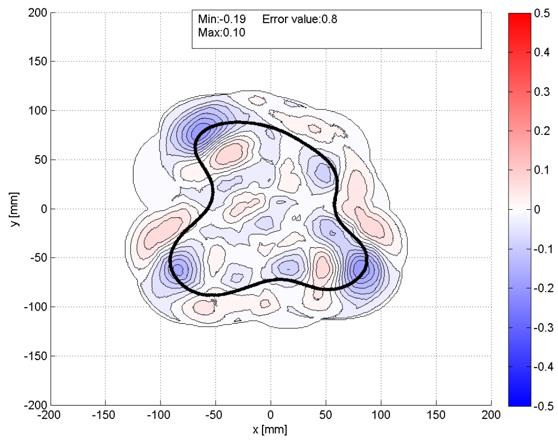


Figure 81: Light field shift 0 mm

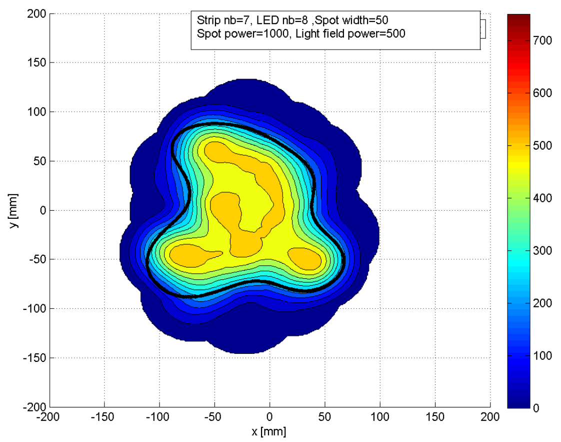


Figure 82: Light field shift 20 mm

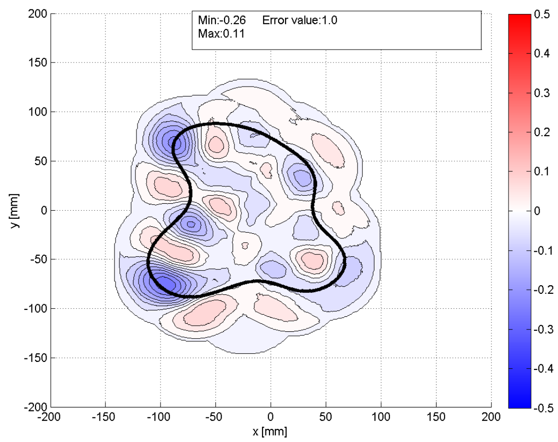


Figure 83: Light field shift 20 mm

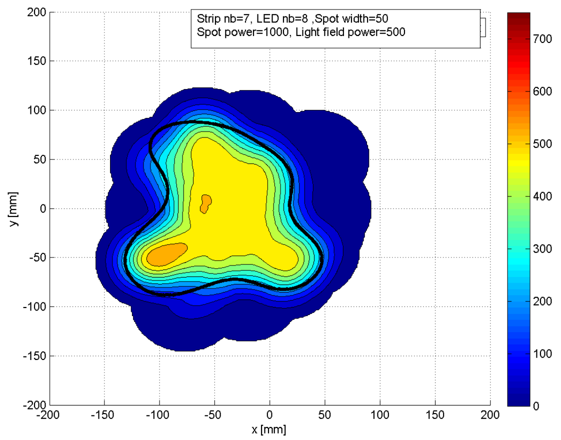


Figure 84: Light field shift 40 mm

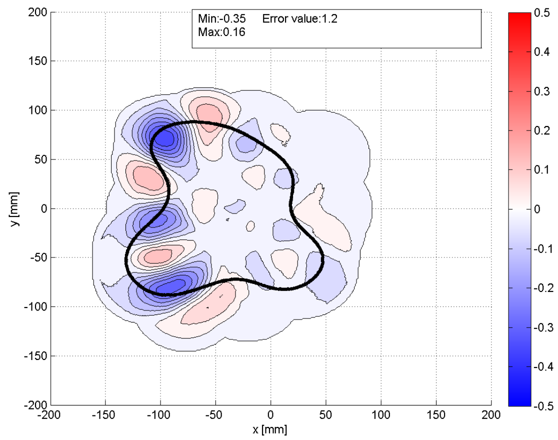


Figure 85: Light field shift 40 mm

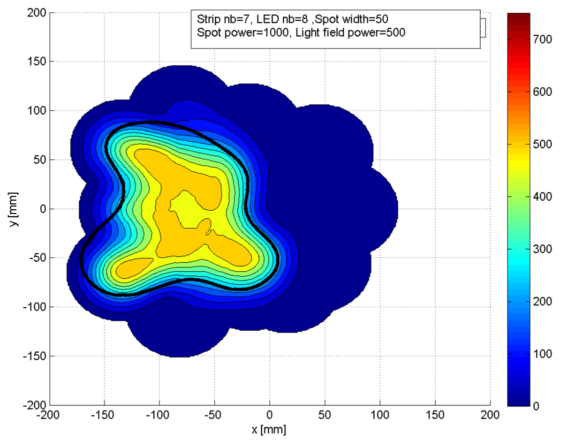


Figure 86: Light field shift 80 mm

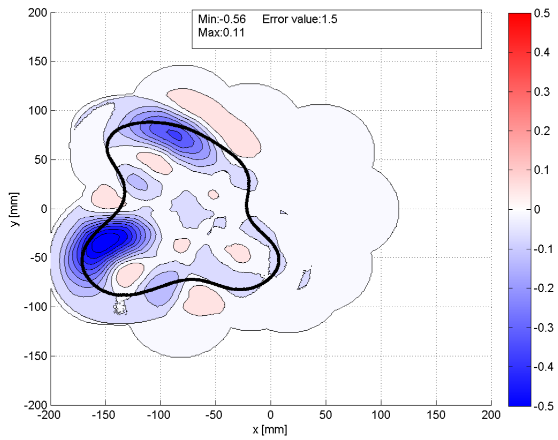


Figure 87: Light field shift 80 mm

Figure 88 shows the effect of the size of the misalignment on the error value. The results seem to be consistent with what can be expected of the effect on the error value. The larger the misalignment, the larger the error. The average control power remains fairly constant with a slight drop at large misalignments. This is probably cause by the reduction in the number of spots that can reach the target light field.

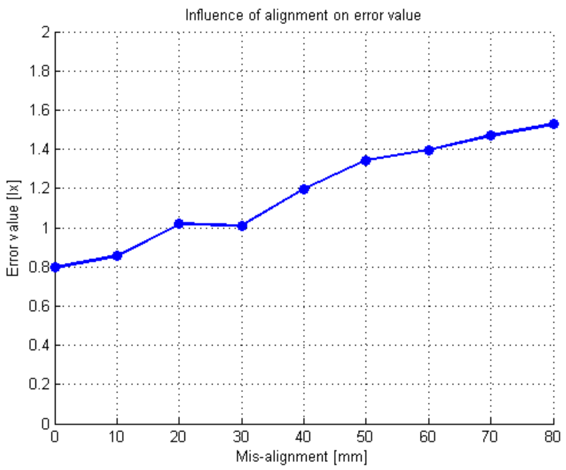


Figure 88: Effect position on error

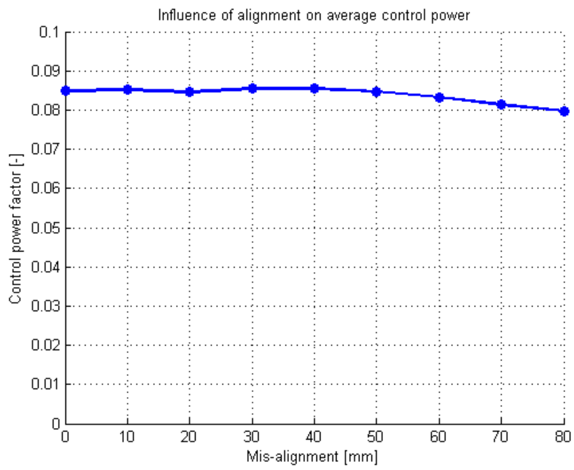


Figure 89: Effect position on control power

Although there is an obvious negative effect of misalignment on the performance of the system, is it clear that system has the ability to compensate for this type of user error.

9.3 Final design

The previous conclusions provide a good basis for the final choices in the luminaire design. A strip number of 7 should be enough to generate most of the input shapes. More strips could in some cases produce even better results, but the increase in performance is not that high to validate the increase in complexity. Each strip will have 8 LEDs attached to it. This way the loading of the strip is as low as possible without drastically affecting the performance. An LED-lens combination should be used that gives a spot diameter of around 50 mm at 1 meter distance. In the following section a Cree XP-C LED will be used that is combined with a Carclo lens that gives a spot width of 62.82 mm at 1 meter distance. This is the narrowest LED-lens combination that is widely available.

10 LightTools

The previous analysis have been done with spot values that have been determined using known values in literature and translating them into light field data. This is an approach that gives clear values, but it could be that in reality other factors will influence the results. The system has been modelled in LightTools to get more insight in how the luminaire system functions in reality. LightTools is a software package that uses models of the real LED-lens combinations and uses them to render light rays that hit a surface which acts as a receiver. This is a very different way of generating the produced light fields.

10.1 Control

The LightTools software is controlled from Matlab. The individual spot locations and orientations that were calculated in the optimisation are used for this analysis. The lightTools code in Matlab connects to the software and translates the coordinates, orientations and power values into instructions that is understood by LightTools. LightTools then starts it calculations and returns the results in the form of a two dimensional matrix. These values are compared with what was received from the optimisations. The software needs special LED-lens files which can be downloaded from the website of the lens manufacturer. The LEDs and lenses that are recommended at the end of the design analysis will be used for this. With this information the software is able to calculate data that comes close to reality.

10.2 Output

It was quite difficult to get proper results from the software. This was for a large part caused by the low resolution of the available data files for the Carclo lens with the chosen Cree LED. Probably the very narrow spot diameter was the cause of the low resolution. This causes a tapered effect inside the light field instead of a smooth result. This has unfortunately affected the outcome and reduced the recognisability of the shapes. A smoothing filter has been applied to the results to make them easier to interpret.

The basic shapes that were used in the design analysis are also used in this analysis.

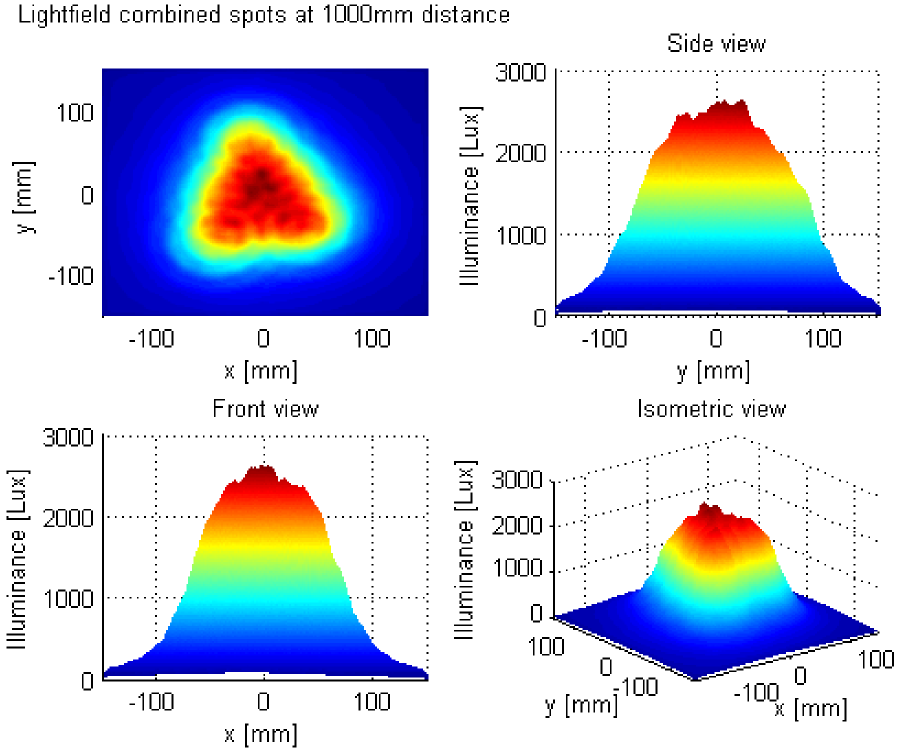


Figure 90: Rendering of an amorph light field

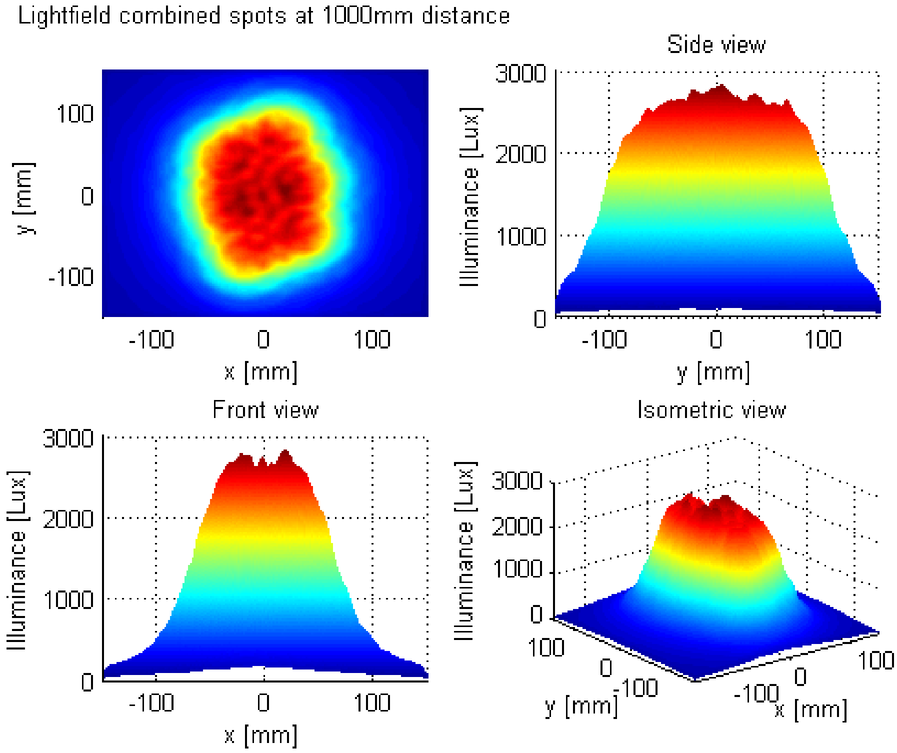


Figure 91: Rendering of an oval light field

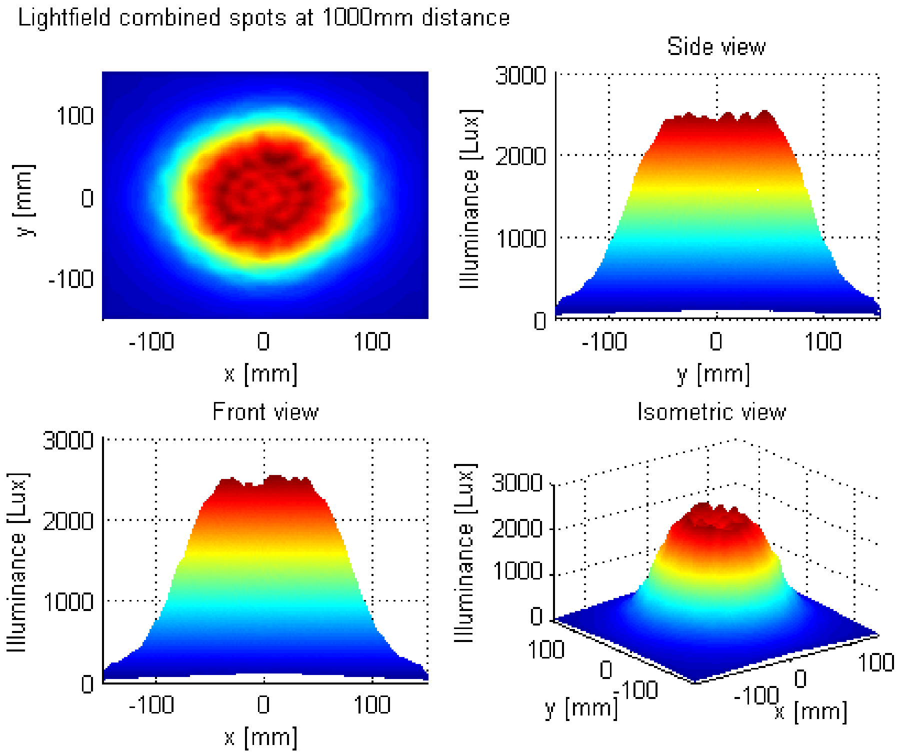


Figure 92: Rendering of a circular light field

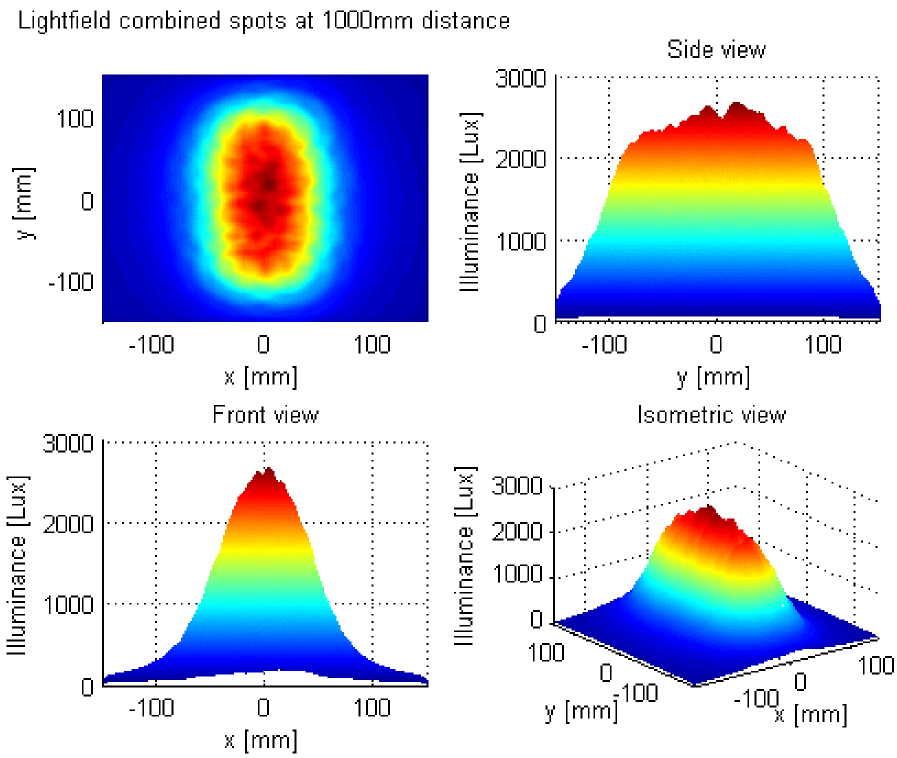


Figure 93: Rendering of a rectangular light field

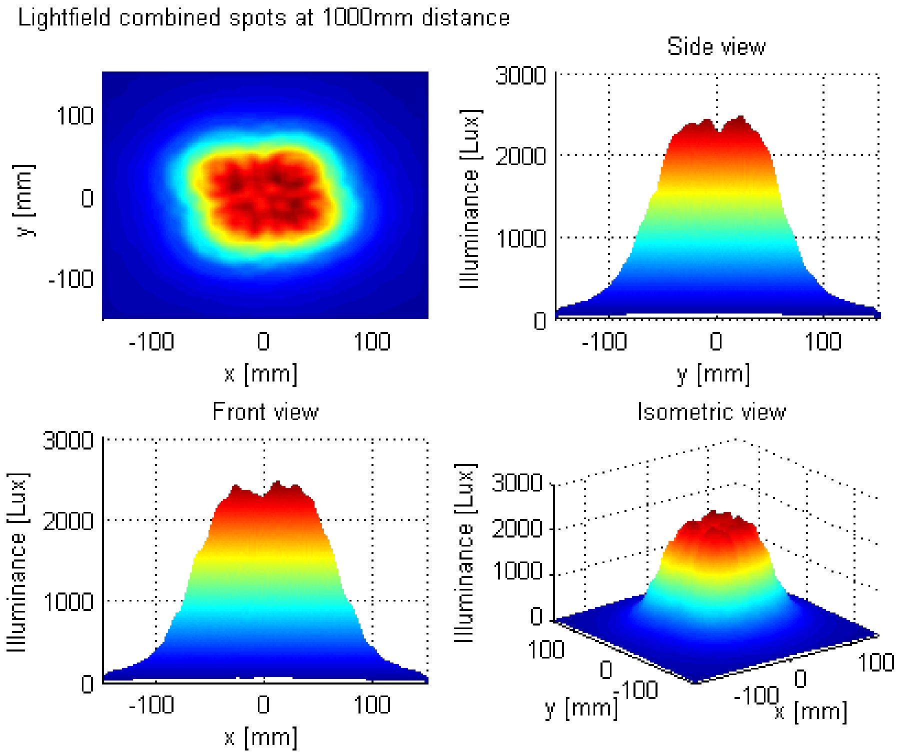


Figure 94: Rendering of a square light field

When looking at the results it is clear that the shapes of the target light field is recognisable in the generated light field. The light fields are however less well defined as the calculated light fields in the optimisation. This is of course to be expected because of several simplifications that were used in the optimisation. It does however seem that the results could have been better if the problems with the software would have been solved.

11 Test setup

So far the luminaire has been modelled using both Matlab and LightTools software. It is important to be able to provide proof that the generated data is valid for a real life situation. An analysis of the light field is done to be see if it corresponds to the calculated values. Several of the non optimal effects are analysed as well. These are the effect of gravity on the strip deformation, the effect of an angled surface on the shape of a spot, the effect of shortened spot distance at large strip angles.
A physical model of one of the strips has been build to be able to provide this proof. The decision to build only one strip and not the entire luminaire is made to reduce the building cost of the test setup. It is not essentially needed to analyse a system with all strips because each strip functions as an individual entity inside the luminaire. The light field that is produced by an individual strips is simply summed with the light fields of the other strips to form the main light field. Another decision to keep the system simple is to modify the shape of the strip by hand. The orientation in space of the strip is done using a tripod. The brightness of the LEDs is controlled using a micro controller.

11.1 Functional overview

The model is designed to be able to position the strip that holds the LEDs over a surface and deform it in a similar way as described in the Matlab models. The intensity of each of the LEDs need to be individually controllable.

11.1.1 Physical model

The physical model is functionally fairly simple. The strip must be able to rotate to set the angle and the curvature must be adjustable by increasing the height in the middle of the strip. When the strip curves upwards, the distal end of the strip must move inwards to allow the deformation. Figure 95 shows these movements.

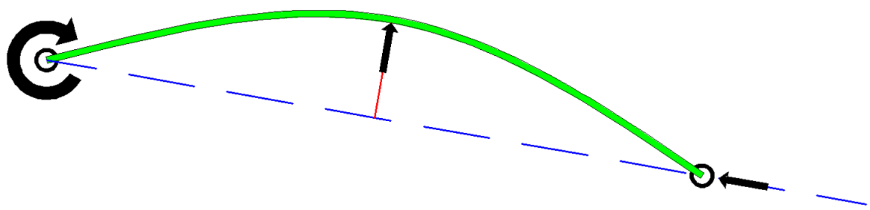


Figure 95: Electronic overview

11.1.2 Electrical model

Electrically there is a little more complexity. Figure 96 shows the main components. There is a main power source that supplies power to the micro controller and to the LEDs. Each LED has a current source that makes sure that the supplied current has the expected value. These current sources are connected to the micro controller which provides a pwm signal that controls the intensity. The micro controller is connected to a computer so the proper pwm signals can be programmed. The camera is also connected to the computer.

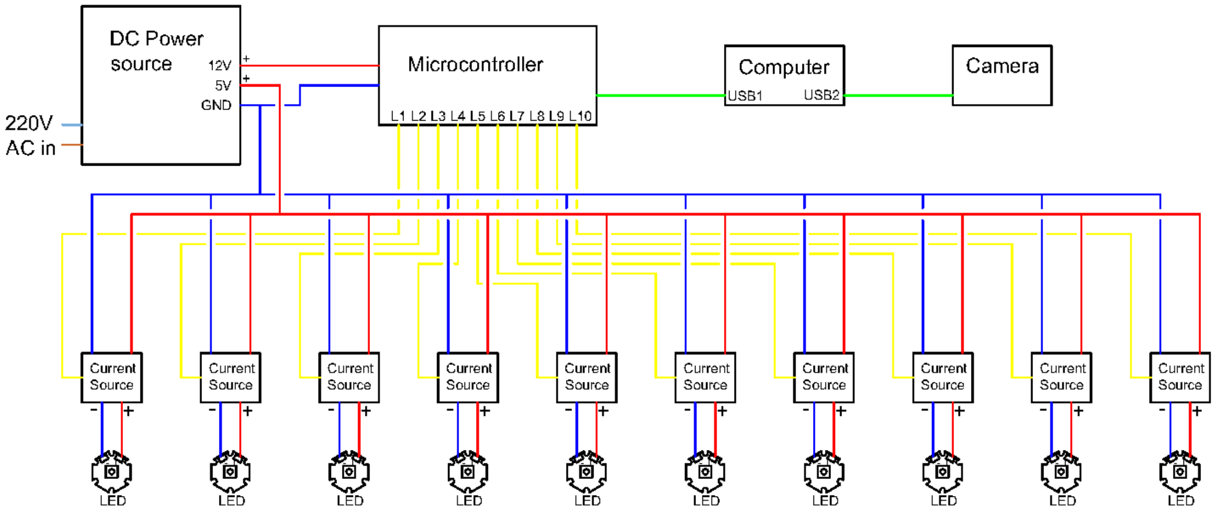


Figure 96: Electronic overview

11.2 Construction

The model is constructed from many different parts. The most important functional parts are described in the following section. Figure 97 gives an overview of the test set-up. Figure 98 gives a close-up of the model. Figure 99 gives a close-up of the underside of the model.

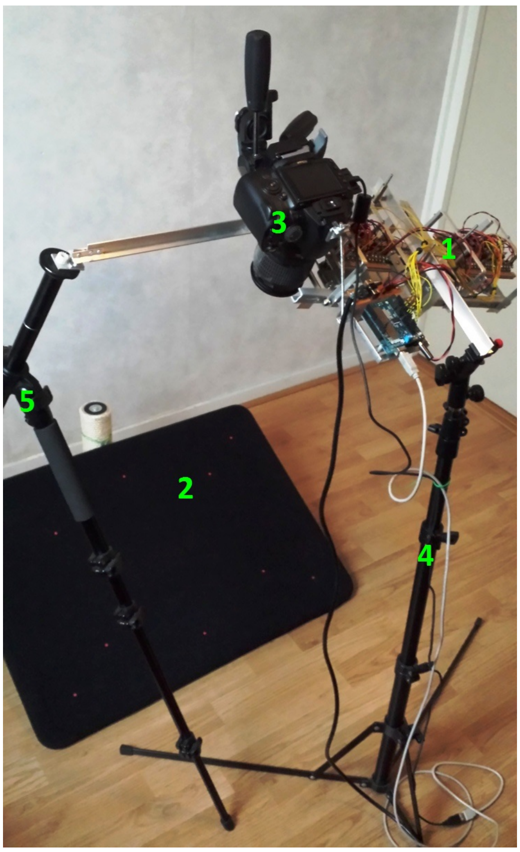


Figure 97: Test set-up (1:Strip model, 2:Target surface, 3:Camera, 4:Model tripod, 5:Stabiliser tripod)

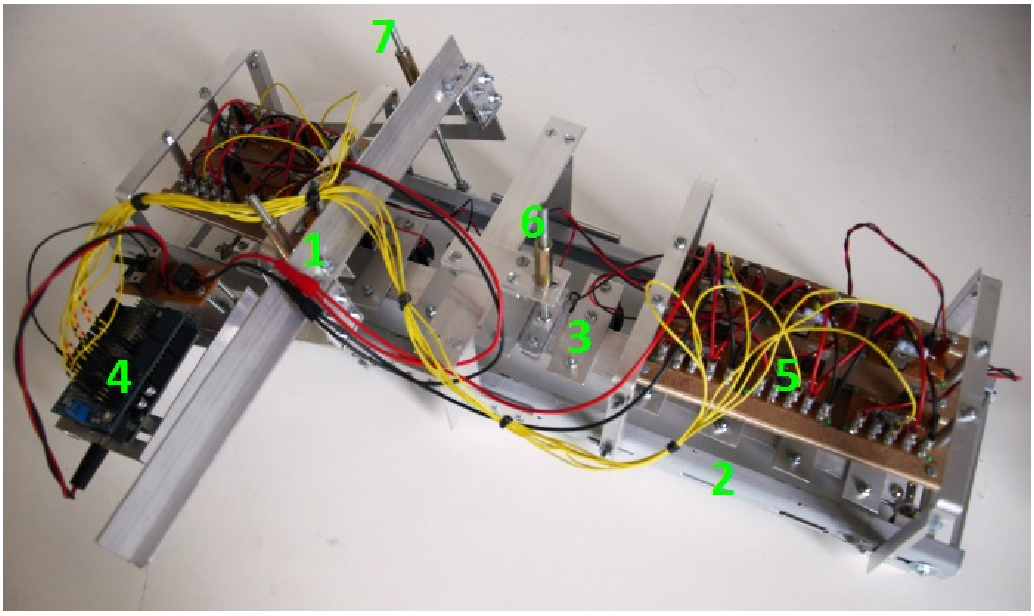


Figure 98: Model top view (1:Stationary frame, 2:Rotating frame, 3:LED holder, 4: Micro controller, 5:Constant current source, 6:Height rod, 7:Angle rod)

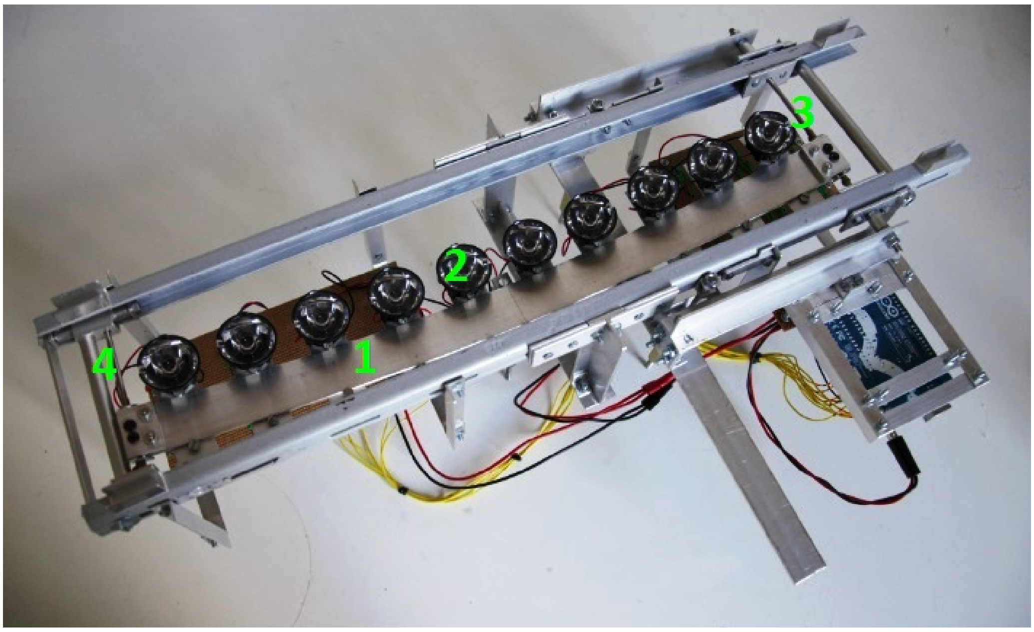


Figure 99: Model bottom (1:Strip, 2:LED-lens, 3:Angle rotation axis, 4:Moving strip endpoint)

11.2.1 Strip

The 400mm long strip onto which the LEDs are mounted is made of aluminium and is 25mm wide and 2mm thick. The strip can sustain the maximum required deformation without the occurrence of plastic deformation. The strip is supported at its endpoints. One endpoint is able to move horizontally to allow the reduction in endpoint distance when the strip deforms. A spindle is connected at the middle of the strip which can be used to set the deformation. This spindle is connected to the rotating frame and a threaded bush is used to set the amount of deformation. The LEDs are connected to the strip by aluminium plates that clamp onto the strip with screws located on both sides of the strip. This way the strip is able to deform freely. This method of attachment places the LEDs besides the strip. The plates can be moved to any location along the strip, except for the middle because that is where the spindle attaches.

11.2.2 Stationary frame

This part of the frame is supported by two tripods to provide a stable base. One tripod is connected by an perpendicular arm to the middle of the frame, the other tripod is connected by an arm longitudinal to the frame. This frame part determines the location of the fixed rotating point of the proximal end of the strip. It also provides a base for the camera and the micro controller. The frame is not directed straight at the ground but at an angle of about 30 degrees. This is done to move the target surface area away from the legs of the tripod as they would otherwise be visible in photograph. The result is that the position of the target light field must be adjust to orientation of the frame.

11.2.3 Rotating frame

This frame part holds the strip. It is able to rotate around an axis that goes though te proximal end of the strip. The distal end of the strip is able to move horizontally within the frame with the use of a slider construction. The angle between the rotating frame and the stationary frame is adjustable with two spindles. Two spindles are used to provide extra stability. The length of the spindle corresponds to a certain angle. This relation has been determined by measuring the vertical displacement of a point on the frame for a range of spindle lengths. The angle of the frame was calculated using this vertical displacement. A line was then fitted onto the data to get conversion formula 6. The stripAngle is in rad and the resulting spindle length is in mm.

$$L_{spindle} = -111.1 * stripAngle + 57.8 \tag{6}$$

11.2.4 Light source

The chosen combination of an LED with a certain lens is a very important aspect of the luminaire system. It is also a very limited choice because it depends on what type of lenses and optics are available. It became clear that most LED-lens systems project a much bigger spot size. Only a few combinations came close enough and of those systems only one type was generally available. The LED light source is a Cree XP-C high power LED with a 26.5 mm Narrow Spot Plain TIR lens from Carclo-optics, both shown in figure 100.

This combination gives a beam angle of 3.6 degrees, which results in a spot diameter of 62.85 mm at a projection distance of 1 meter. This is only a little larger than the target 50 mm that was used in many of the optimisation calculations.

The Cree XP-C has a luminous flux of 67.2 lm. This is for an high power LED a fairly average output. The light is focussed in a narrow beam, which gives a maximum luminous intensity 10k candelas, or 10k lux at 1 meter. During the design analysis it became clear that for a medium size light field a target luminance of 2x the output of a single LED is an achievable value without increasing the error value. The required luminous intensity of the light field is 40k lux. This means that LEDs are not power full enough to achieve the target luminous intensity in a 7 strip and 8 LED system. If these LEDs were to be used in the final design it will be necessary to use more LEDs, or change the positions of LEDs on the strip so less LEDs are located in the middle of the light field. The minimum distance between two LEDs is 3 cm for this particular lens system. 10 LEDs are placed on the strip for this test model, which fits easily. The LEDs are soldered to standard star shaped printed circuit boards. These PCBs provide a good basis to attach the lens using a lens holder and they can be easily attached to the plate that will be connected to the strip.

(a) Cree XP-C LED (b) Carclo lens

Figure 100: Used LED and lens combination

11.2.5 Current source

The luminous flux that is produced by the LED will depend on the supplied current. The characteristics for the LEDs that are used in the test setup are given in figure 101. Although this relation can be used to control the intensity, it is preferred to use pulse width modulation to do this as it gives a linear relation and is easily implemented using a micro controller. The supply current to the LED during the experiment will be 350 mA, which is the typical supply current for this type of LED. The relative luminous flux will be 100% at this input current. Because the luminous flux of an LED is so strongly influenced by the supply current, it is important to be able to provide accurate current value which is equal for each of the LEDs. A standard power supply where a resistor is used to set the current does not provide the required accuracy, so a more advanced constant current source will be used. A cheap solutions for this was found online ((5)). This scheme can be seen in figure 102. Each LED will have its own power source which is constructed using several cheap components. Q2 is a power NFET transistor that functions as a variable resistor. The main current will flow, from the LED, through this transistor and resistor R2. When the current gets above a certain value, the NPN transistor Q1 gets activated and it shuts off Q2, stopping the current flow. This functions as a feedback loop that continuously monitors and controls the current value. R1 has a high resistance so there is a small current flow when Q1 is switched off, but when Q1 is activated it is able to overpower the current flow through R1. The current level is determined by R2. The Zener diode Z1 is meant to provide current when a micro controller is used that runs on 3.3 volts. 3.3 Volts is not enough to switch Q2, so a Zener diode that provides 5 volts is used. When the PWM signal is low, the current from the Zener flows through the micro controller to ground. When the PWM signal is high the current flows to Q2. This way any connected PWM signal is able to switch the current.

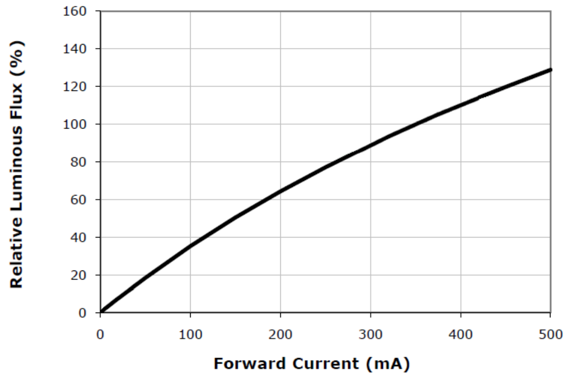


Figure 101: Relation between the relative flux and the supplied current. Junction temperature is 25 °C.

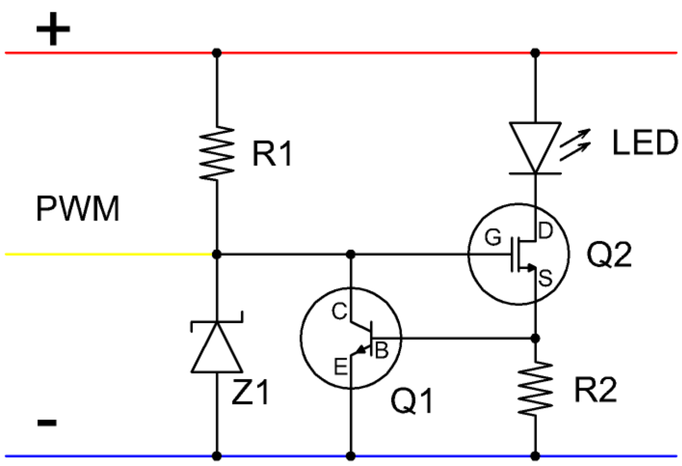


Figure 102: Power source schematics

11.2.6 Micro controller

The micro controller that is used is an Arduino Uno. This is a relatively cheap open source platform that is easy to program. It has all the functionality of performing the required control task. During construction it became clear that the Arduino by itself did not have enough power to generate a PWM signal for all LEDs simultaneously. An Adafruit PWM/servo shield is used to generate all 10 signals. This shield can be placed on-top of the Arduino and provides the needed power. The controller is connected to a computer and programmed using Arduino software. The controller is set to create a pwm wave at a frequency of 800Hz. This is frequency is fast enough to be flicker free and does not conflict with this type of LED. The pwm signal is programmed with a single line of code that determines the channel of the specific LED, the tick time when the pulse should go high and the tick time when the pulse should go low. One pulse is 4096 tick long, so the intensity can be very accurately controlled. The program runs in a loop that continuously generates the programmes pulses.

11.2.7 Camera

The used camera is a Nikon D5000 with a 18-105mm lens which was set at 35mm for all photographs. The camera is attached to the stationary frame. A tripod head with three degrees of freedom is used

to determine the direction of the lens. A spindle is connected between the top of the camera and a second point of the stationary frame. This is done to increase stability.
The camera is connected to the computer with camera control software digiCamControl. The camera settings are controlled with this software and the photographs are automatically taken and uploaded to the computer. The ISO is set at 200 for all photographs, which is the standard value for this type of camera. The aperture is set at f11 for all photographs. At this setting the distortions are low for this type of lens at 35mm. The Shutter speeds are either 1/2 sec, or 1/4 sec. Compared images are always taken at the same shutter speed.

11.2.8 Illuminated surface

The surface that will be photographed is a rectangular plastic cover with a black cloth spanned across it. Black is used to reduce the intensity of the light field which allows for a wider range of possible camera settings without saturating the camera's sensor. Dots are placed onto the target surface to be able to measure distance and to point the camera in the proper direction, see image 103. There is a total of 10 dots on the surface. 6 dots specify the outside of the frame. Their position and distance to each other is know so they can be used to estimate distances inside the photograph. The horizontal distance between the S-coded spots is 30 cm and the vertical distance 40 cm. Another 4 dots are placed inside the frame. These C-coded spots are used to determine the direction of the camera. The viewfinder of the camera has lines that cross the frame (green lines in the image). These are used to centre the 4 dots.

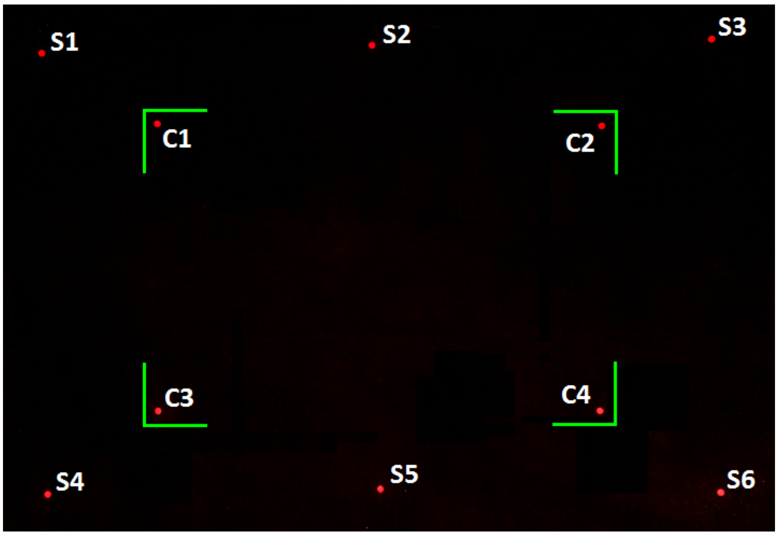


Figure 103: Target surface

11.3 Heat dissipation

Although LEDs are known for there high efficiency, they still produce heat that needs to be dissipated away from the LED. Not only is there a risk of damaging the LED if the temperature gets to high, the temperature of the semiconductor die also influences the actual luminous flux, as can be seen in figure104. The LEDs will be dimmed using PWM, so a LED that is powered with a higher average value will produce more heat than a more dimmed LED. This will result in a difference in drop in luminous flux if the heat isn't dissipated properly. Another part of the lighting circuitry that produces heat is the constant current source. As can be seen in figure 105, the LED has a forward voltage of 3.2V at 350mA. It is not possible to connect the LEDs in series, since it must be possible to dim each LED individually. Therefore the constant current source will only power a single LED. The N-Channel power MOSFET passes the right amount of power to the LED, but will have to turn the remaining power into heat. An ATX power supply is used to provide power to the constant current source. This type of power source has a choice between 3.3V, 5V and 12V. The 3.3V would result in very little excess power that needs to be converted, but does not leave much room for inaccuracies cause by component precision ranges and efficiency losses. A 5V supply would result in a heat production of about 0.63W. This heat is dissipated through the heat sink of the power Mosfet. If the heat isn't disposed off properly then the Mosfet can get damaged.

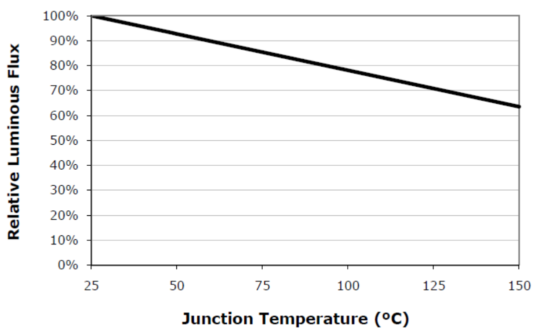


Figure 104: Influence of the LED temperature on the luminous output

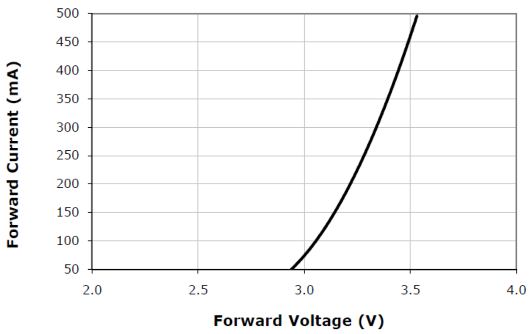


Figure 105: Relationship between forward voltage and supply current

11.4 System inaccuracies

Any system has inaccuracies, but because this test model has been build by hand with very basic tools are the inaccuracies relatively large. The following section describes some of the main inaccuracies. These are important to interpret the output of the model and also to predict if a production model would perform differently.

Construction The model has been constructed by hand, without the use of high precision tools. This means that there will be relatively large dimensional variations in the construction. Not all variations will have a large effect on the functionality but some will. For example a variation in the direction of an LED will be exaggerated because of the distance to the light field.

Frame stiffness The frame is made of steel and aluminium. Because of the weight of the system it will bend under loading. The parts that will show most deformation will be the aluminium beams that connect the model to the tripods. Modifying the angle of the strip will shift the centre of gravity, which influences the deformation. This results in a shift in the location of the light field.

LEDs The very small LEDs are soldered by hand to star shaped circuit boards, which is done through reflux soldering. This means that the contacts of the circuit board are tinned in advance. The LEDs are then placed in the proper position and the entire board is heated to the point that the solder melts and a proper connection forms between the contacts of the LED and circuit board. During this process it is very well possible that the LED was exposed to temperatures that were in excess of the allowed soldering temperature. This might affect the luminous properties to the LED. Another factor that could cause a variation is the amount of solder that is used, which can cause a difference in the position or direction of the LED.

Lens holders The holder that positions the lens above the LED had to be modified because the lens was placed to far away the LED. This resulted in a beam angle of around 10 degrees instead of the promised 3.6 degrees. The four legs of the holder have been shortened. This introduces a variation that has influence on the diameter of the spot and the direction of the spot. The lens holders are now glued tot the LED holders. When the alignment of the lens and the LED is correct then the bright central spot will be in the middle of the large halo that surrounds the spot. This is checked by eye when glueing the lenses tot the LEDs.

Power source The power sources consists of several components. These components determine the actual output of the power source. Each component will have a functional bandwidth in between which they will work. A 100 Ω resistor with a 1% bandwidth can be in between 99Ω and 101Ω These differences will cause slight variations in the supplied current. Also difference in temperature of the components can influence the functioning of the light source.

Positional arrangement During modifications like changing the strip angle it is inevitable that the positions of the individual components change relative to each other. The positions and orientations are checked by eye in-between modifications

Component temperature Several components produce heat during operation. This heat influences the functioning of the device, so it would be preferable to do the test when component temperature is as constant as possible. This can be done by activating the system for a certain amount of time before the photograph is taken, so the component heat up to a constant state. The problem with the current system is that the power limits of the micro processor almost reach its maximum allowable value due to the high number of connected components. This means that powering the system for a long time could destroy the device. Therefore it was decided to only activate the system for very short periods. This should reduce the temperature difference between components as much as possible.

11.5 Test procedure

It is important to make sure that as little variations as possible exist between consecutive measurements. The following procedures should minimize these variations.

11.5.1 Preparation

Ambient light To make sure that the image of the light field represents the created light field as close as possible, it is important that the ambient light is homogeneous and has a low intensity. The intensity of the ambient light will influence the ability to differentiate between light levels inside the projected light field. It is also important that the ambient light is constant when several images need to be compared.

Strip position The strip inside the frame is positioned using the tripods that support the static part of the frame. It is placed at an angle leaving enough room to position the illuminated surface at 1 meter.

Target surface The target surface is flat and has an even black colour. It must be perpendicular the direction of the camera and must be parallel tot the horizontal axis of the strip. The proper alignment is checked with a measuring tape and a water level tool.

Camera position The camera is positioned in such a way that is is pointing straight at the surface. The lens is located next to the middle of the strip, in such a way the strip is outside the frame.

11.5.2 Manual adjustments

Angle The angle is adjusted so the strip orientation matches the modelled height. This has influence om the system, so after adjustment it is necessary to check the positions.

Curvature The curvature is adjusted so the curve height matches the modelled height.

Power The power of each LED is adjusted by changing the PWM setting of the designated ports on the controller.

11.6 Imaging

The photograph that is taken from the light field is used to analyse the intensity distribution and compare this with the data produced by the Matlab calculations. The photo has to be post-processed to be able to compare the data. To get reliable results, it is important to follow a proper procedure that determines how te photo is handled during post-processing.

11.6.1 Camera settings

To be able to compare the photographs, it is required that each photograph is taken under the same conditions and with the same settings for shutter speed and ISO value. The chosen settings must give an exposure bandwidth that can capture the brightest setting without over-lighting the image. An image that is to dark is also not good because then the resolution to differentiate between the light levels becomes to coarse. Different types of analysis can use different settings, but it is important not compare the images with images from the other setting.

11.6.2 Post-processing

The photographs need to be taken in RAW format. This format holds the sensor readout without any post processing done to it. Information about the camera, which is needed during post processing, is also stored in the file. The camera that is used in this experiment is a Nikon D5000. This camera stores the RAW files in the proprietary format NEF. To be able to load these files in Matlab it is needed to convert them to Adobe's open file format DNG. Adobe provides software that converts the file to DNG format without modifying the sensor data. The file is then loaded into Matlab and converted as described in (6). The main steps in this process are:

Linearisation Nikon applies non-linear transformation to the sensor data for storage purpose, which has to be linearised. The required linearisation table is found in the meta data of the RAW file

White balancing The colour channels need to be scaled to get a proper representation of white. The correct values for black and white are also stored in the meta data of the RAW file.

Demosaicing The sensor data is recorded and stored in the typical Bayer pattern which has pixels that are either red, green or blue. This mosaic-like pattern needs to be converted to the regular colour space values where each pixel has a red, green and blue value. The demosaicing function of Matlab is used to do this.

Convert to BW To be able to compare the image to the calculated Matlab data which was generated during the optimisation process, it is necessary to convert the triple layered colour image to single layered grey-scale values.

Scale pixels The photographs are compared with the modelled data. In these calculated images, one pixel corresponds to one mm. Therefore the data is resized so the scales are equal. The dots on the target surface are used to measure the pixel distance in the photograph and this is used to calculate the conversion factor to mm.

Apply blur filter The images are not very smooth due to the texture of the target surface and the presence of reflective dust specks. This makes it hard to compare values, like the maximum intensity, between images. A blur filter is applied to the images to reduce the local variations. A Gaussian filter is applied with a dropbox size of

The proposed procedure in (6) incorporates several data manipulations that were not beneficial for this experiment. During the demosaicing step a normalisation is performed on the data . This is done to increase the bit depth of an individual image, but it would also mean that an image is no longer comparable with another image. Another undesirable step is the conversion to sRGB. This conversion is meant to display the image properly on a computer screen. The photographic data will be compared with computer generated data and not visually, so this conversion would only preform an unneeded alteration of the colour values. Also the proposed brightness and gamma corrections are not performed since they are intended to make the image look good to a human observer.

11.7 Results

The data inside the images vary between 0 and 1, where a value of 1 would mean that the sensor was fully saturated. This means that there is no real correlation between the image and the actual luminous intensity of the LED. The values of the image are multiplied by a certain factor so the maximum value of the image is equal to the maximum value in the data

11.7.1 Photograph consistency

To be able to compare the photographs it is important to have an idea about the variation in the photographs. To measure this several photographs with the same LED intensity value have been taken. To increase the chance of variation several other possible causes of variation were incorporated. The first and second photograph were taken in quick succession. The 3rd was taken after 1 minute while the LED was switched on continuously. The micro controller was switched off and on between the 3rd and 4th photograph and the camera was switched off and on between the 4th and 5th photograph. The resulting maximum values were very close to each other. The mean power value was 0.26714 and the average variation was 0.00062 with a maximum variation of 0.00142. This means that the variation caused by imaging is very low and not an issue during the procedure.

11.8 LED consistency

The individual LEDs should have comparable intensities when activated by the same PWM signal. To test this, a photograph has been taken of the light spot created by each of the 10 LEDs. The maximum intensity values are compared in figure 106. The blue line represents the intensity values when each LED is fully powered. It is clear that there is a fairly large variation between the individual LEDs, especially the 3rd LED is much more powerful than the others. This can be caused by several factors. It could be that the LEDs were heated to much during the reflux soldering and got damaged. Another reason might be that there is a variation in the position of the lenses. It is also possible that there is a manufacturing variation in this type of LED. It will be necessary to compensate these variations by lowering the activation power of the brighter LEDs so they are levelled with the weakest LED, in this case LED 7. A reduction factor for each LED is calculated and applied to the PWM signal. The green line shows the intensity values after this equalisation step. Figure 107 shows the variation of the power values before and after equalisation.
The shape of the created light spots can be seen in figure 108. There is some variation in the shape of the individual spots. Some spots have a larger low intensity halo around the bright centre. When comparing these images with the maximum intensities of figure 106 it seems that the LEDs with a relatively small low intensity halo, like LED 3,4,8 and 9, have a higher peak value. The shape if the spot is primarily influenced by the position of the lens. This seems to indicate that the variation in peak power originates from variations in the lens position.
The width of the spots have been measured by hand. This was done by tracing locations where the intensity was 50% of the peak value. These values were measured in the x and y direction and averaged to compensate for elliptical spot shapes. The values for each LED are shown in figure 109. The values vary a little, but overall they are fairly consistent. The average FWHM is 63.3mm, which is very close to the 62.9mm which was specified by the manufacturer. The equalisation step has no effect on the spot width.
The LEDs are simply mounted to the strip and do not have advanced features to calibrate the direction of the beam. This means that the positions of the individual spots along the target surface will have an error compared to the expected locations. This error can be seen in figure 111. The blue dots represent the measured real locations of the spots and they are much less evenly spread compared to the calculated positions. The effect of this, is that there is a variation in the amount of overlap between

spots. This will have the effect of an uneven light field. The positional errors in y direction will also have influence on the width of the light field, because the spots are no longer placed along a line, but in a certain surface area. It is not easy to solve this problem for this model, but a final design should have a calibration feature for each LED.

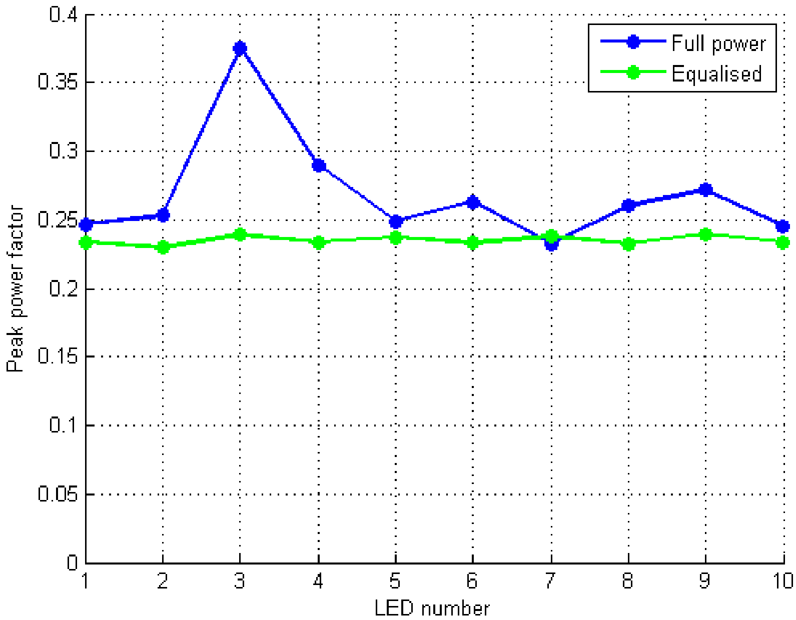


Figure 106: Maximum intensity value of each LED. The blue line is at full activation power. The green line is after equalisation.

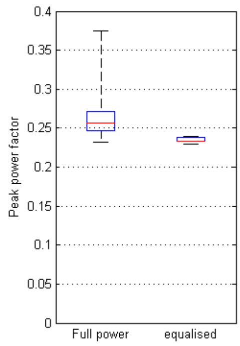


Figure 107: Variation in the maximum LED power

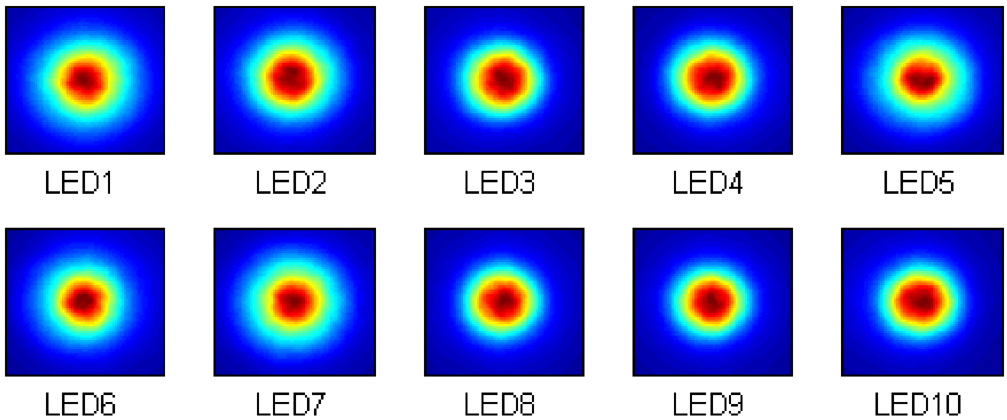


Figure 108: Spot shapes of all 10 LEDs

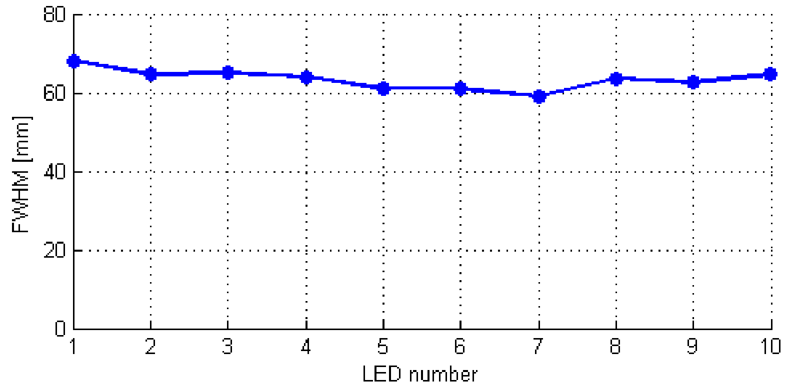


Figure 109: Measured diameter of the individual spots

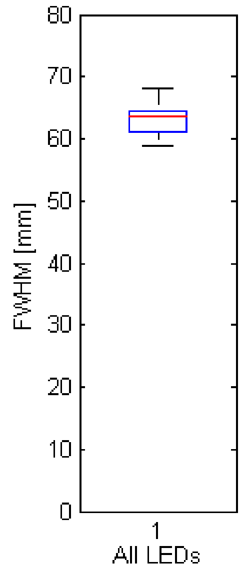


Figure 110: Variation in the spot diameter

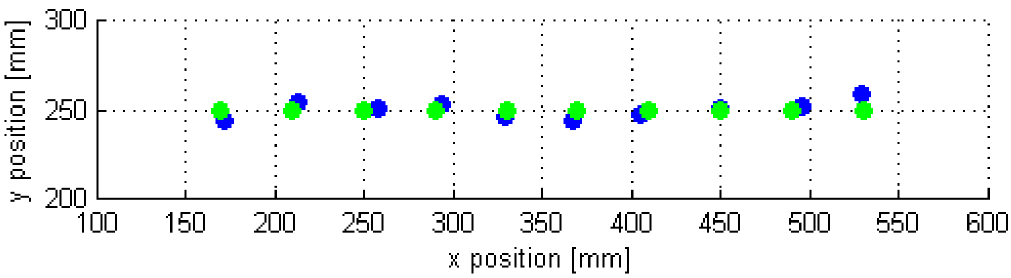


Figure 111: Positions of the spots along the target surface. Green is the calculated position and blue the actual position.

11.8.1 LED intensity

The intensity of the LED is controlled using pulse width modulation. In theory the intensity of the LED should respond linearly to linear changes in the PWM frequency. A single LED has been activated at a range of PWM settings to test if the response is as expected. Figure 112 shows the results. The activation factor indicates what portion of the pulse the LED is activated, so 0 is turned off, 0.5 the signal drops in the middle of the pulse and 1 is fully activated. The peak power represents the maximum measured value inside the photograph. The green dotted line is a fitted straight line through the measured maximum values.

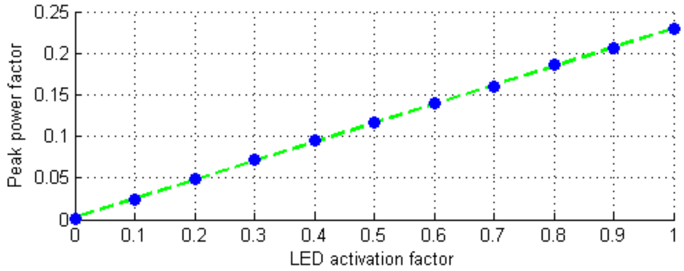
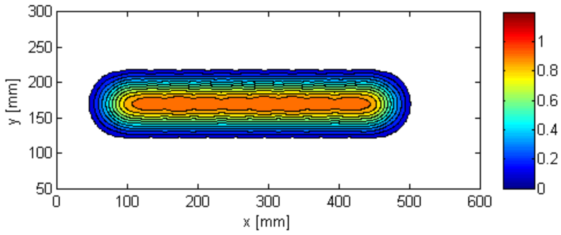


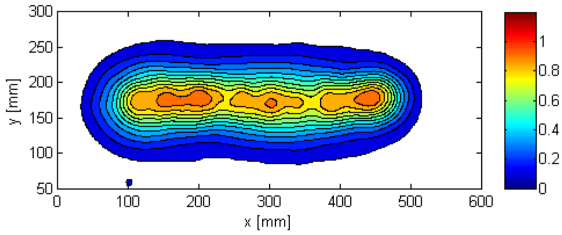
Figure 112: LED intensity at increasing PWM activation values

11.8.2 Strip curvature

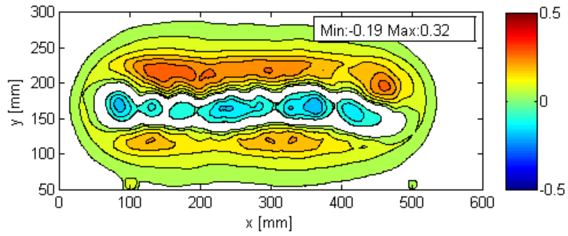
The curvature of the strip is a very important mechanical aspect of the way the luminary will function. The effect of the curvature on the resulting light field has been calculated in Matlab, but it is always possible that errors were made because there are many different calculations needed to come the resulting effect. Simplifications in the computer model are another possible cause for errors. The following figures give an overview of the comparison between the calculations and the light field that is produced by the test set-up. The light field is positioned more or less in the middle of the target surface with an angle of 15 degrees. The power of the LEDs is at full power for the equalised situation. The results are normalised to the maximum of the calculated light field.



(a) Calculated light field



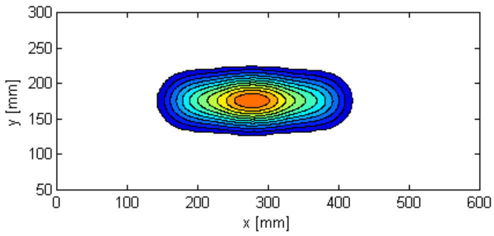
(b) Photograph



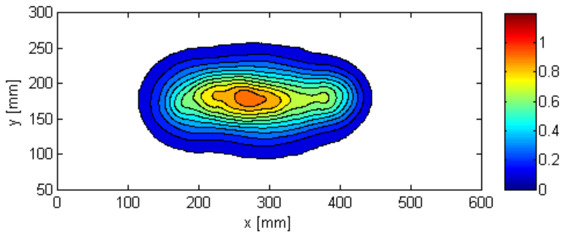
(c) Error field

Figure 113: Light field comparison at curve height 0mm

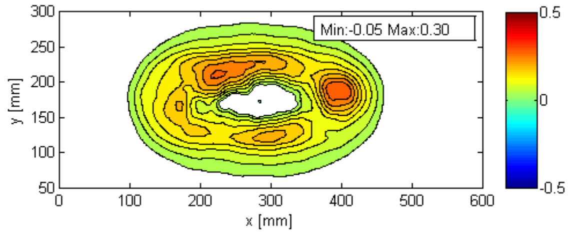
The first setting is set at a curve height of 0 mm, so the strip is completely flat. This gives a very long light field, as can be seen in figure 113. The light field that was created by the system does not look as smooth as the light field created in Matlab. This is mainly caused by the directional errors of the LEDs. The result of these errors is that some spots overlap more than others, which causes a higher intensity value on one side of the spot and a lower intensity value on the other side. It is also clear that the light field is a little bit wider in vertical direction that the computer generated light field. This is caused by the slightly wider spots and also misalignments of the LEDs in y direction. The resulting error field clearly shows these differences in width and smoothness.



(a) Calculated light field



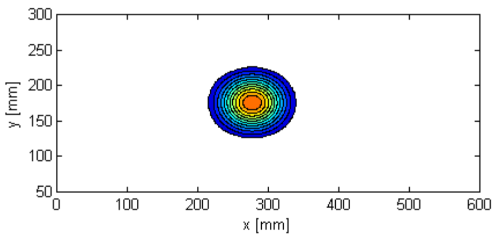
(b) Photograph



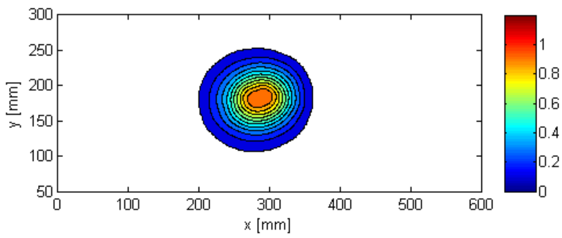
(c) Error field

Figure 114: Light field comparison at curve height 10mm

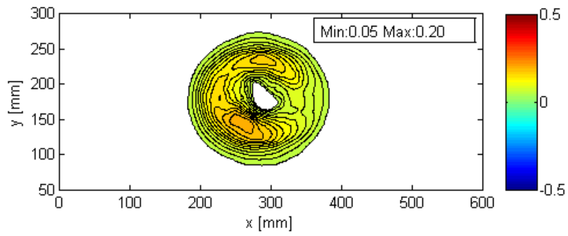
Increasing the curve height to 10 mm moves the spots closer together. This improves the smoothness of the light field. There is still clearly a difference in the width of the LEDs. The resulting error field shows that there are no longer areas where the intensity is lower than the calculated value.



(a) Calculated light field



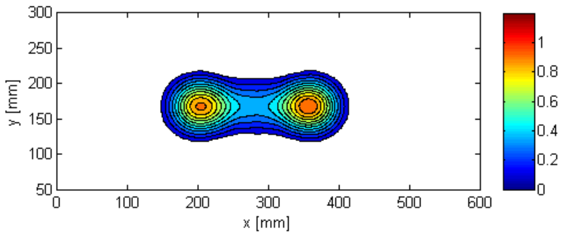
(b) Photograph



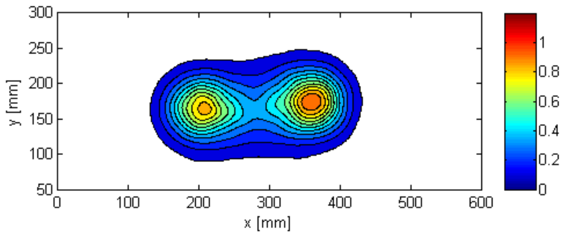
(c) Error field

Figure 115: Light field comparison at curve height 22mm

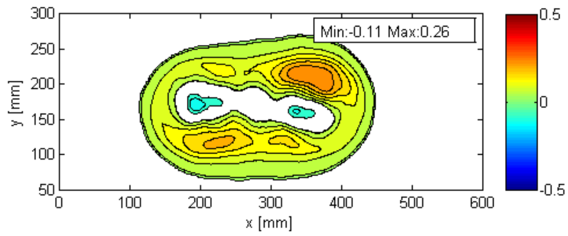
A curve height of 22 mm causes the LEDs to almost coincide, resulting in a circular light field. The light field that is created by the model is as expected a little bigger than the calculated light field due to misalignments and a wider spot width. The maximum value in the error field is further reduced.



(a) Calculated light field



(b) Photograph



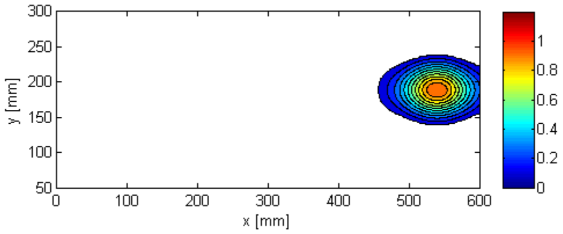
(c) Error field

Figure 116: Light field comparison at curve height 35mm

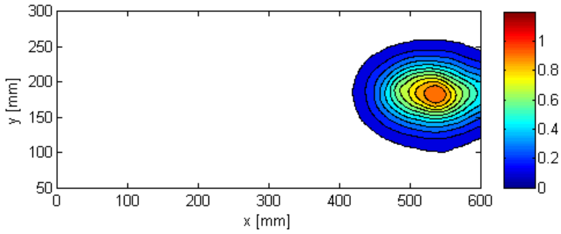
Increasing the curvature to 35 mm causes the LEDs to move away from the centre. They spot directions coincide in mid air. The created light field has a two higher peak values at the left and right side of the light field. This is caused by the sine like deformation shape. LEDs at the beginning and end of the strip are less strongly affected by the deformation. Another effect that can be seen in the created light field is that the peak on the right is stronger than the peak on the left. This is caused by the angle of the strip which brings one side of the strip closer to the target surface. This effect can be seen in both the calculated light field and the photograph.
The comparison between the computer generated data and the photographs show generally very comparable results. The effect of modifying the curve height shows similar functionality.

11.8.3 Strip angle

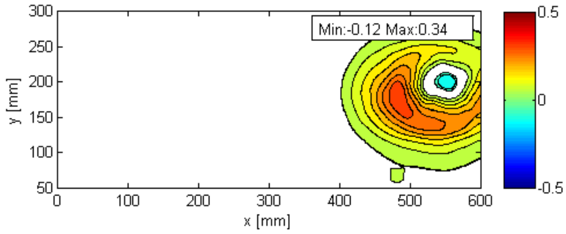
The angle of the strip determines the location of the light field on the target surface. This is a mechanical procedure that causes large displacements of the components. This makes it a challenging analysis for the test set-up, because there are many factors that influence the results. Examples are the shift in gravity which causes the model to bend differently and an error in rotation axis which moves the light field in a different direction than the expected direction. Another problem was cause by the connection of the camera to the frame. The movement of the model pulled on the stabilisation spindle, which caused an offset in the direction of the camera. This camera orientation error was difficult to solve, so it is compensated digitally by measuring the offset of the 2nd and 5th surface dots. This offset was used to align the images.
The results can be seen in figure 117 to 119. The light field is moved from right to left. The curve height was 15 mm and the LEDs were at full power.



(a) Calculated light field

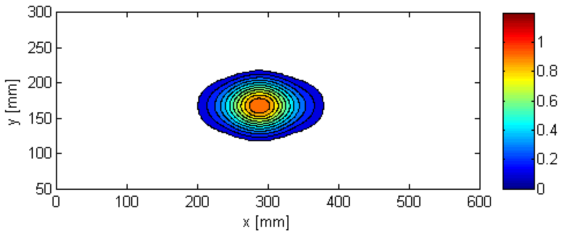


(b) Photograph

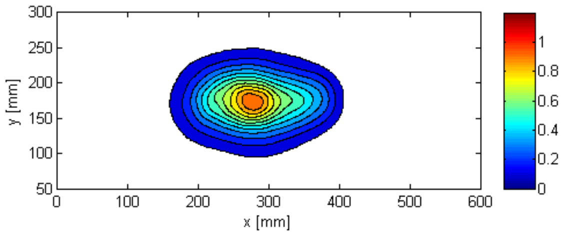


(c) Error field

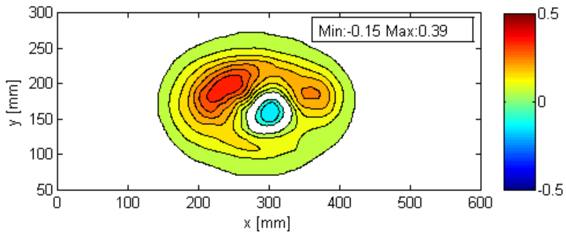
Figure 117: Position light field at a strip angle of 0 deg.



(a) Calculated light field

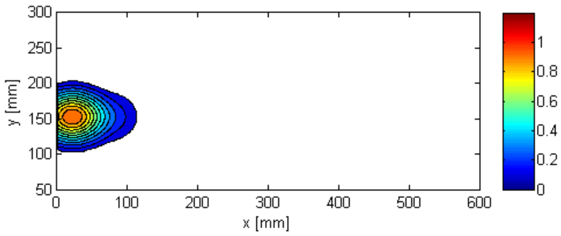


(b) Photograph

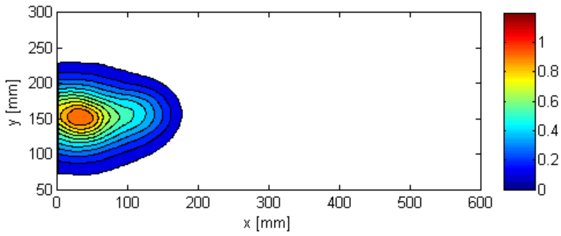


(c) Error field

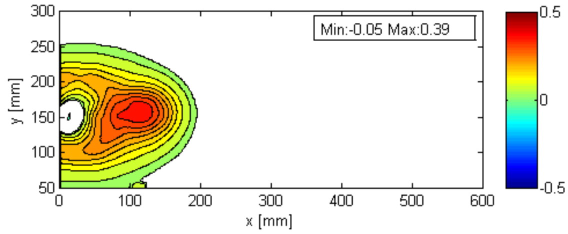
Figure 118: Position light field at a strip angle of 15.5 deg.



(a) Calculated light field



(b) Photograph

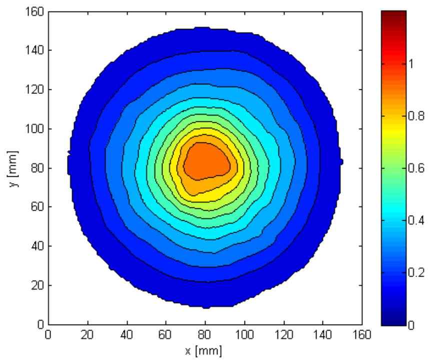


(c) Error field

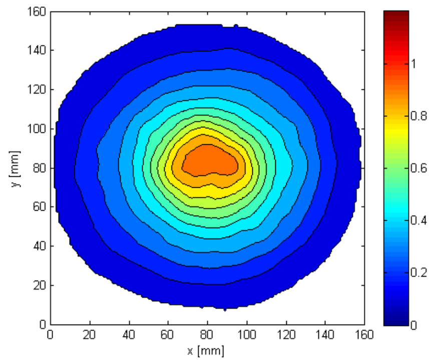
Figure 119: Position light field at a strip angle of 29.8 deg.

The produced light field is follows a similar path as the calculated path of the computer. There are minor differences in location which can be seen in the error fields. The peak in error value is on the left side of the centre at 0 deg, but it is on the right side when the angle is 29.8 deg. This can be explained by the sift of the gravitational centre of the model. When the angle is bigger, the torque in the frame reduces, so the deformation also reduces. This causes the light field to be projected more to the right.

An effect of the angle that has not been incorporated in the optimisation calculations in the Matlab, is the ellipse effect when a spot is projected at an angle. The Matlab model always uses circular spots. A photograph has been taken from a single spot when the direction was perpendicular to the surface and one of the same spot, but with a strip angle that moves the spot to the far edge of the target surface. The angle of the strip in this situation is 30 degrees. The result can be seen in figure 120



(a) Straight angle



(b) 30 degree angle

Figure 120: Angle effect on the shape of spot

It can be seen that spot widens in x-direction under an angle. The width in y direction is not affected. The effect is not very large under the expected angles that the system is going to make.

12 Requirements review

This section will discuss the individual requirements that were stated at the beginning of the report.

12.1 Light field related requirements

- The smallest possible diameter of the light field should be $<$150mm when projecting a circular shaped light field.The luminary must be placed at a distance of 1 meter.
- The largest possible width of an oval shapes light field should be at least $>$300mm.
- The smallest possible width of an oval shapes light field should be at least $<$100mm.
- When lighting an oval shaped wound with a length of 300mm and a width of 100mm, the area of the light field should be smaller than $0.18m^2$. This area corresponds to an oval light field of 400mm by 150mm.

These requirements all address the size of the light field. In principle these shapes can be made with the current design, depending on the chosen size of the spot. The mainly used light fields in the optimisation have a smaller size, so smaller spots can be used.

- The wound border must fall within the border of the light field.
- The error between the projected light field and the desired light field must not be larger than 15% on average.
- The border of the light field should be able to produce shapes with a smallest border radius of at least 50mm.

The ability of the system to trace the border were very good. The errors are in most cases within the required margins.

12.2 Light related requirements

- The colour of the light must be uniform along the light field and remain in the desired color space.

The system uses LEDs with a single colour. This means that the colours will be uniform along the light field.

- The intensity distribution must be 80% accurate compared to a desired shape which follows from the user input and predefined shape models.

The system showed to be able to produce a very constant and flat distribution inside the light field.

- The intensity may not exceed 160 kLux at the brightest spot of the light field.
- The device should be able to illuminate 50% of the inside of the predefined wound shapes at an intensity of 40 kLux.

- The total radiance of the luminary may not exceed 1000 W/m^2 at 1m distance.

These requirements depend on the chosen LED and the number of LEDs used. The LED that was used during the experiment will be able to reach 40 kLux when enough LEDs are used. Exceeding 160 kLux is something that is easily avoidable because there is much control over the intensity. The radiance is not likely to be exceeded when using this type of light source.

- The shadows must not introduce noticeable uncommon distractions.
- The surgeon's head may not produce excessive shadows and pass the tests which are specified in the current standards for surgical luminaries.

The system consist of many different light sources, so shadow dilution is generally good. Because the system can dynamically switch LEDs on and off it will even be possible for other LEDs to increase their intensity in the case some are blocked.

- The light must not produce noticeable flickering or other instabilities.

LEDs can be very stable when using the proper hardware. Flicker free illumination was achieved in the test model.

- The light should not produce unnecessary glare.

The system is designed to be able to avoid areas that could produce glare.

12.3 Design requirements

- The device must be small enough to manoeuvre with relative ease and no longer than 1.5m.
- The total weight of the device should allow it to be suspend by current arm systems.
- The device should not extensively disrupt the laminar airflow.
- The device should be easy to clean.
- The device should not contaminate the patient with dust or other particles.

These requirements are related to current system dimensions. The shape of the designed system is very similar, so should not perform worse on these items.

- The system should not be highly complex.

The system is certainly more complex that current systems. The increase in complexity is however not excessive given the amount of functionality that has been added.

- There must be a manual control function.
- In manual mode the device must comply with current standards.

Manual control over the shape is probably not advisable since that is going to introduce a large workload to the surgeon. Having a manual mode that emulates current systems is very well possible. That means only adjusting the intensity and focus point.

– Operating the luminary should be intuitive.

Drawing a shape with the input device and then letting the device create the light field is highly intuitive.

– The light should remain functionally operational in case of an failure.

When something goes wrong internally, it should be possible to have the system go into manual mode with basic controls.

– Energy consumption should remain acceptable.

Energy consumption of LEDs is relatively low.

– The device should not produce distracting noises.

The noise that the system makes can only originate from the motors that will modify the shape of the strips. Using high quality motors should reduce noise levels.

13 Conclusion

During the project it became clear that many different aspects come into play when a system is designed that can modify the shape of a light field. The basic idea of placing LEDs on a bendable surface is very simple and elegant. From this simple idea a system evolved with many different subsystems and variables that all influence the functionality in their own way. Each subsystem on its own is not complex, but the complexity comes from the interdependency between them. It was clear that each subsystem had to be examined individually to see the influence it has on the system. During these analyses the abilities of the system became visible. The system is able to produce light fields that can have fairly complex shapes at a good range of different sizes. It was possible to give recommendations about aspects like spot size and strip number. Both the LightTools model and physical model indicate that the calculated system seems to function in a way that is close to how it would in a real-life situation. Given the results it can be concluded that a system, which is able to modify the light field in real time and that requires minimal control effort, can be a good addition to the operating room.

14 Discussion

Although the analysis shows promising results, the design is far from being a fully optimised device.

14.1 Design improvements

14.1.1 Alternative spot shapes

Standard circular spots with a Gaussian distribution were examined during this research, but it is very likely that further improvements could be achieved when additional shapes and or sizes are used. Some light field shapes can benefit from this, but for others it might be a negative effect. A research on commonly encountered wound shapes can provide valuable information.

14.1.2 Additional spot locations

Using a radial alignment of strips will result in a high concentration of spots axis in the centre of the light field. The spot concentration is lower towards the edges. It is possible to place additional LEDs in certain locations on the luminaire that can provide extra light field coverage. There is space in between the strips to place these LEDs. A simple solution could be fixed LEDs that can be turned off is they are focused on an area where no light is needed, but also more complex solutions are possible. The disadvantage is that it will make the system more complex.

14.1.3 Variable spot size

The current fixed spot size limits the system to cope with various light field sizes, causing irregular light distribution along the central area of the light field. If the spot size is able to increase in diameter when a larger light field is required, then the overall smoothness of the light field will increase. To achieve this, the lenses in front of the LEDs will have to be actuated. This increases complexity of the system. It is possible to design a system where the spot size for all LEDs on a single strip are controlled with one actuator. This will be a less complex system compared to control over each individual lens, but will still be beneficial because in the case of a large shape, all LEDs need a change in spot width. It will increase the weight and size of the components that are connected to the strips, so it must be done properly.

14.1.4 Alternative strip deformation

The strips use a very basic deformation to position the LED spots. Using other deformation shapes will have effect on the spot distribution inside the combined light field. These different deformation shapes can be achieved in many ways, for example applying a bending moment on the end of a strip, using a strip material that is not uniform in thickness, forced deformation with an extra actuator, etc. One of the disadvantages of the current deformation shape is that there is no setting where all spots coincide in the light field. This means that the smallest possible size light field is bigger than the spot size.

14.1.5 LED locations on the strip

With the current evenly spaced configuration of LEDs on each strip, many spots in the combined light field are located in the centre of the light field. This is often the location where the highest brightness is required in the case that a non uniform light field is required by the surgeon. On the other hand will this configuration lower the maximum illumination near the edges of larger light field shapes. If the system is unable to provide the required intensity, is it possible to place more LEDs towards the ends of the strip and fewer in the middle.

14.2 Software improvements

The software at the moment has many limitations. This needs to be improved to come to a functional device.

14.3 Real-time calculations

This research shows the potential of the system. To be able to use the system in the operating room, it will be necessary to have a system that produces a proper light field very quickly. The optimisation process is by far to slow for this. Technically the created light field comes from a summation of Gaussian curves over several axes. It should be possible to create a smart program that does this fast enough.

14.3.1 Luminaire placement

The current design has been analysed with the luminaire placed directly above the surgical area, directed straight down towards the target surface. A fully functional surgical luminaire will also be placed at an angled orientation. This will have to be implemented in the software. This addition will require extra angles to be incorporated in the spot location calculations. Also the effect that circular spots become elliptical when the illuminated surface is at an angle will also have to be taken into account.

14.3.2 Exclusion areas

The current system matches the light field to a single input shape. It might be beneficial to add an option where the surgeon can point to a location that needs to be excluded from the light field. This could be the location of a highly reflective object inside the wound for example.

14.3.3 Camera feedback

The input system now does not makes use of an automated feedback system. Adding a camera inside the luminaire could provide valuable information about the actual light field and where improvements are needed. During the experiment with te modelled strip is became clear that using a simple analysis it was very easy to calculate accurate normalising factors for the power of the LEDs. Such features could improve performance without adding workload to the surgeon.

14.4 Additional research

Not all properties of the system have been analysed properly. The following items may need further research or testing.

14.4.1 Performance tests

The theory is that applying a better fitting light field shape will reduce difficulties in the visual task. Whether the performance indeed increases can only be tested in real life under strict conditions.

14.4.2 Shadow dilution

Current systems that project a basic circular light field have good shadow dilution properties. In the case of a surgical luminaire that uses multiple LEDs, each LED focusses on the same location. When the light from one or more LEDs is blocked, the light from other LEDs will still reach the surface. This dilution property is reduced when the individual spots are used to control the shape of the combined light field. Fewer spots are determining the illumination distribution near the edges of the light field, so each LED that is focused at a border region has a larger share in the illumination of that particular area. This means that ff a certain beam is blocked, especially if that beam that is focused towards a shape edge, there will be a more noticeable reduction in illumination at the shape edge.

14.4.3 Non flat surfaces

The target surface that is used in this analysis is flat, but the wound of a patient isn't. The effect that the system has on deeper wounds need to be analysed. It is likely that the luminaire output needs to be modified to compensate the intensity reduction. These effects can be modelled in software like LightTools, or it can be done through experiments.

15 Declarations

Many different design choices will have to be made to come to a proper functioning luminaire system. To be able to start the design process in a structured manner and to limit the amount of variables, it is needed to declare some of the system parameters at the start of the design process.

Surgical area To reduce complexity, the surgical area is defined as a flat surface with a two dimensional wound shape. This means that the complex geometrics of the wound are not part of the design process.

System origin The system origin is placed centrally in the surgical area. When symmetry axis exist inside the wound shape, the origin coincides with these axis.

Luminaire origin The luminaire consists of several radially aligned strips. The luminaire origin is located in the middle of the proximal ends of the strips. Seefigure

Luminaire orientation The luminaire has a position and rotation in relation to the system origin. The

General setting In general cases the luminaire is placed at a distance of 1000 mm above the origin. The luminaire is not rotated along any axis, so [x,y,z,

Target light field The target light field is defined as a flat two dimensional shape. The surface is parallel to the horizontal plane of the luminaire. The central focal point of the luminaire falls inside the target light field.

Projection axis Each strip can modify the location of the spots by changing the curvature and the angle. This will move the spots along a straight line inside the light field. This line is referenced as the projection axis of the strip.

Strip length The length of a single flat strip is 400 mm. This means that the luminaire system will have a diameter of around 1 meter.

Strip orientation The strips are placed in a radial alignment, much like a star shape.

Luminaire distance The luminaire origin will be located at a distance of 1000 mm from the system origin. This

16 Function and image references

$EndPD$	[mm]	Distance between the two endpoints of the strip.
$Lstrip$	[mm]	Length of a flat strip.
α_{strip}	[deg]	Angle of the strip that is used to position the strip light field inside the combined light field.
H_{curve}	[mm]	Height of the curved strip, measured in the middle where height is maximum.
W_{strip}	[mm]	Width of the strip material
T_{strip}	[mm]	Thickness of the strip material
$Emod_{strip}$	N/mm2	
σ_{spot}	[-]	Standard deviation that determines the circular Gaussian light distribution of the light source.
I_p	[cd]	Peak power. Maximum luminous intensity in the centre of the spot.
θ_{beam}	[deg]	Beam angle. Property of the light source that determines the spot diameter at a certain distance.

17 Abbreviations

FWHM	[mm]	Full width at half maximum. Spot width where the intensity has dropped to half maximum, often referred to as the spot diameter.
cd	[cd]	Candela. This is the SI base unit for the power of a light source in a specific direction.
sr	[-]	Steradian or solid angle. It is a representation of a conical section of a sphere. A sphere contains 4π steradians
lm	[cd*sr]	Total amount of visible light that is emitted by a light source. The sensitivity of the human eye for certain wavelengths has been taken into account.

18 Terminology

System state The physical configuration of the luminaire. This depends on all the endpoint distances and angles of the strips. The needed input parameters are calculated using the input image from the surgeon. They system state is achieved by actuating the strips accordingly.

Input parameters These are parameters that control the system state. Each strip has an endpoint distance and strip angle. Each LED has an intensity. The entire set of parameters determine the combined luminary output.

Surgical area The surgical area is the small region where the surgical luminaire is the primary light source.

location where the surgical procedure takes place. The luminaire only has to illuminate this region. This area includes the wound and exposed skin as well as the part of the surgical drapes that also fall inside the light field.

Light field The shape of the light field is determined by the surface area that is illuminated at 50% or more of the maximum illumination value.

Focus point The focus point of an LED is the point in the centre of its light field. The used LEDs create a

Spot axis The imaginary line inside the target light field over which a strip can position the LED spots.

Curve height Deformation distance of the middle of strip compared to a flat strip.

Proximal strip end The strips are placed in radial alignment. The proximal end is the end closest to the centre of the luminaire.

Distal strip end The strips are placed in radial alignment. The Distal end is the end closest to the edge of the luminaire.

19 Formulas

19.1 Strip calculations

Equation for the area moment of inertia of the strip.

$$I_{strip} = \frac{1}{12} W_{strip} {T_{strip}}^3 \tag{7}$$

Equation for the strip deflection

$$y_{strip}(x) = P\frac{x}{48EI}(3{L_{strip}}^2 - 4x^2) \tag{8}$$

$$y_{strip}'(x) = \frac{P(3{L_{strip}}^2 - 4x^2)}{48EI_{strip}} - \frac{Px^2}{6EI} \tag{9}$$

Equation for the height of a point on the strip

$$H(x) = H_{curve} * sin(\frac{\pi}{EndPD} * x) \tag{10}$$

Equation for the arc length of a segment of the strip

$$s = \int_a^b \sqrt{1 + (\frac{\mathrm{d}y}{\mathrm{d}x})^2} \tag{11}$$

Equation curve length of a point on the strip

$$L = \int_0^x \sqrt{1 + (H_{strip} * \cos(\frac{\pi}{W_{strip} * x}) * \frac{\pi}{W_{strip}})^2} \tag{12}$$

19.2 Spot calculations

Equation for the spot diameter at a certain distance.

$$width = tan(angle) * surfaceDist * 2; \tag{13}$$

Equation for Gaussian spot

$$power(x,y) = peakpower * \exp(-\frac{x+y}{2\sigma^2}) \tag{14}$$

Equation to convert spot width to Gaussian sigma $\sigma = \frac{FWHM}{2\sqrt{2\log 2}}$
Equation for ellipse shape of spot for angled surfaces

19.3 Electrical calculations

Equation for the heat production inside the N-Channel power MOSFET $P_{Q2} = I_F * (V_{PS} - V_F)$

19.4 Test setup

$$I_{strip} = \frac{1}{12} W_{strip} {T_{strip}}^3 \tag{15}$$

$$rodDistance = -111.1 * stripAngle + 57.8 \tag{16}$$

References

[1] [NEN-EN-IEC 60601-2-41, 2009,Medical electrical equipment(2009). Particular requirements for the basic safety and essential performance of surgical luminaires and luminaires for diagnoses.

[2] William C. Beck, (1971), Lighting the operating room- criteria and choice .

[3] William .C.Beck, (1980),Choosing Surgical Illumination

[4] Eda Emirdag, 2011,Collecting Relevant Environmental Parameters for Surgical Lighting Control, (2011)

[5] Dan Goldwater, (2009),High Power LED Driver Circuits, D. Goldwater,(2009). notehttp://www.instructables.com/id/Circuits-for-using-High-Power-LED-s/?ALLSTEPS

[6] Processing RAW Images in MATLAB

Appendices

A Arduino code example

```
// Based on the an example file for the Adafruit 16-channel PWM/Servo Shield.
// See adafruit.com for more details.
#include <Wire.h>
#include <Adafruit_PWMServoDriver.h>
Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver();

void setup() {
  Serial.begin(9600);
  Serial.println("10 channel LED control");
  pwm.begin();
  pwm.setPWMFreq(800);  // 1600 is the maximum PWM frequency
  uint8_t twbrbackup = TWBR; // save I2C bitrate
  TWBR = 24; // set I2C bitrate
}
// Set the PWM frequency. setPWM(channel, on, off)
//
void loop() {
  pwm.setPWM(9,0,4095*0.7835);
  pwm.setPWM(8,0,4095*0.6585);
  pwm.setPWM(7,0,4095*0.8236);
  pwm.setPWM(6,0,4095*0.8329);
  pwm.setPWM(5,0,4095*0.6245);
  pwm.setPWM(4,0,4095*0.7000);
  pwm.setPWM(3,0,4095*0.4039);
  pwm.setPWM(2,0,4095*0.7542);
  pwm.setPWM(1,0,4095*0.7069);
  pwm.setPWM(0,0,4095*0.9915);
}
```