Programming and Verification of an Optical Measurement System for LCD Cells

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Programming and Verification of an Optical Measurement System for LCD Cells

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Abstract

A LCD (Liquid Crystal Display) consists of two glass substrates glued together with a small gap (called cell gap) in-between them. The gap is filled with a liquid crystal. To produce a display with good viewing characteristics it is very important that this gap, and other parameters, gets the right dimension. There are formulas that can be used to calculate which cell gap that is appropriate in which application. The problem is that it does not exist any realized methods that can measure the parameters of the LCD cell to decide if the LCD is useful or not in an early state of the production.

A number of theories has been presented on how to measure and calculate these parameters but no really working systems has been presented. This Master’s thesis describes how such a system can be implemented. The system is based on the theories of S Valyukh of the Swedish LCD center and it is using a modified version of the Nelder-Mead Simplex Algorithm.

The tests done in this paper indicates that the system has the potential to be commercially useful. However more extensive tests and some modifications must be carried out before it can be really useful.

Programmering och verifikation av optiskt mätverktyg för LCD-celler

Sammanfattning


Ett antal teorier har presenterats för hur man skulle kunna mäta och beräkna dessa parametrar men inget praktiskt fungerande system. Detta examensarbete beskriver hur ett sådant system skulle kunna implementeras. Systemet baserar sig på teorier från S Valyukh från Swedish LCD center och använder en modifierad version av Nelder-Meads simplexalgoritm.

Det test som gjort i denna rapport indikerar att systemet har potential att kunna bli kommersiellt användbart. För att nå dit kommer det emellertid att krävas mer utförliga tester samt att några modifieringar görs.
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Chapter 1

Introduction

This chapter gives a short introduction to LCDs and a short presentation of Conoptics and the Swedish LCD Center is given. The aim and delimitations of this master’s project are also presented.

1.1 Short about LCDs, Conoptix, and Swedish LCD Center

LCD stands for Liquid Crystal Display. The LCD-technique is used in a wide range of applications that have use for a display. A LCD can be quite simple as in for instance the display in a sun powered calculator or wristwatch, it can also be more complex as in flat computer or TV screens. To put it simple, a LCD consists of two glass substrates with a liquid crystal in-between.

The Swedish LCD Center is a research institute for the benefit of Sweden’s LCD producers. The Swedish LCD Center focuses on the development of new technology and production methods for transfer to the industry. The idea with this is that it shall provide opportunities for improved efficiency and new areas of application for LCD technology.

Conoptix is a small company that buys and aims to commercialise ideas and methods developed at the Swedish LCD Center. That is also the case with the measurement system that this Master’s project is a part of.

1.2 Aim and Method

The aim of this Master’s project was to find and implement an algorithm that can be used by an optical measurement system that is under development by Conoptix. The system performs measurements on Liquid Crystal Displays (LCDs) during production and development. To put it simply the system uses a computer controlled spectrometer to measure the cell gap (the distance between two glass substrates) and other parameters that are of interest. The algorithm was intended to find these parameters using optical theories.

The chosen algorithm and implementation was then evaluated in order to find out if it is possible to use it in a commercially useful system. Some proposals for improvements and future work are also given.

The method of this Master’s project was to search for an existing algorithm that could be adopted and or modified to be useful for this specific problem. A more appropriate method might have been to implement a number of different algorithms and then compare them. However the limited time for this project made that impossible.
1.3 Delimitations of the Master’s Project

The Master’s project focuses on finding a method that can be useful for finding certain parameters that can be of interest when producing or developing LCDs. To do this different numerical methods are used. The different methods are built on advanced physical and optical theories and equations. These theories and equations are not being verified or derived in this paper. When used, all such theories and equations are assumed to be physically correct.
Chapter 2

Background

This chapter gives a short introduction to the physical principles on which the LCD-technique is based. Readers with knowledge in this area can skip this chapter.

2.1 The nature of light

Light can be considered as a stream of particles or a wave depending on how the experiment is arranged. In some cases the stream of particles is the most obvious, in other cases the wave nature is. When discussing liquid crystal displays, the wave nature is the most appropriate description to use. Hence in this paper, light will be viewed upon as a transversal electromagnetic wave. The electromagnetic wave is characterised by frequency, wavelength, polarisation, amplitude and speed [4]. The frequency is the only parameter that is independent of the media that the wave is travelling through and it also decides the colour of the light. However when talking about light it is more common to talk about its wavelength rather than its frequency. The wavelength then refers to the wavelength in vacuum.

Unlike other waves, electric and magnetic oscillations of an electromagnetic wave occur in numerous planes. A light wave which is oscillating in more than one plane is referred to as unpolarized light. Light emitted by the sun, a lamp, or a candle flame are examples of unpolarized light. Such light waves are created by electrical charges oscillating in multiple directions, thereby creating electromagnetic waves vibrating in a variety of directions. Unpolarized light can however be transformed into polarized light, where the light waves oscillates in a single plane, by a process known as polarization, see figure 2.1.

![Figure 2.1 An unpolarised beam of light travels through a polarizer. After the passage the beam is polarized which means that all oscillations occur in a single plane. Figure source [4].](image-url)
Polarization of light can be achieved in a number of ways, one of the most common is through absorption. A polarization filter (a polarizer) can be described as a disc made of long coloured threads arranged in parallel rows. All the oscillations in a light beam that are directed towards the polarizer, except those parallel to the threads, will be absorbed. If two polarizers are placed perpendicular on top of each other hardly any light can pass, see figure 2.2.

*Figure 2.2 If, as in the top picture, two polarizers are placed parallel to each other the beam of light can pass. In the case when two polarizers are perpendicular to each other no light can pass. Figure source [4].*

The speed of light differs in different media for example speed of light in vacuum is approximately 300 000 km/s, in water 225 000 km/s and in glass 200 000 km/s. When light travels in a denser media the wavelength will be shorter compared to traveling in a less dense media whereas the frequency is always the same. The refraction index of a media is the ratio between the speed of light in vacuum and in the media. That gives glass a refraction index of approximately 1.5.

Transparent materials can be either isotropic or anisotropic. An isotropic material has the same optical characteristics in every direction whereas an anisotropic material will show different characteristics in different directions. This is true for so called birefringent materials. In birefringent materials light will have different refraction indexes for different polarization directions which means that the light will have different wavelengths and different speeds in two perpendicular polarization planes, see figure 2.3. Since the light waves in the two polarization planes will be dislocated in relation to each other the direction of the polarization will be altered. There are a number of examples of birefringent materials, for instance different types of plastics. In some birefringent materials with regular structure it is possible to achieve a controlled change of the polarization direction of the light that passes it. This is used in the process of manufacturing Liquid Crystal Displays (LCDs).

*Figure 2.3 In a birefringent material the light will travel at different speeds in different polarization planes. The picture shows two perpendicular light waves that will have different wavelengths due to the birefringence. Figure source [4].*
2.2 Liquid Crystals

Most materials exist in three phases: solid, liquid, and gas. The solid phase can either be crystalline or isotropic. Crystalline means that the molecules are ordered in a strict three dimensional pattern and isotropic means that the molecules are unordered. Usually when a solid crystalline substance is heated it transforms into an isotropic liquid. When the substance is cooled again and solidifies, it recovers its crystalline structure. The molecules in liquid crystals however are still somewhat ordered even in the liquid phase. Liquid Crystal (LC) materials change their appearance with temperature like other materials, but in the liquid state the molecules of a LC are still somewhat ordered. In temperatures below the melting point, \( T_m \), the materials are solid, crystalline and anisotropic, the molecules are ordered in a strict three dimensional pattern. Above the clearing temperature, \( T_c \), they are a clear isotropic liquid much like any other regular liquid. In the temperature range between \( T_m \) and \( T_c \), however the LC materials have the appearances of milky liquids; in this state the molecules have more freedom of movement than in the solid state but they are still not completely free as in the isotropic state.

The anisotropic liquid state can be divided into three major phases (more phases exists see Bahadur, 1990 [5]) the smectic C, smectic A and the nematic phase see figure 2.4.

![Figure 2.4](image)

*Figure 2.4 The most common phases of Liquid Crystals. From left: Crystalline, Smectic C, Smectic A, Nematic and Isotropic. A Liquid Crystal will transform from one phase to the next with increasing temperature. The Nematic phase is the phase most often used in LCDs. Figure source [5].*

The molecules in the smectic C phase are ordered in two dimensions, they are arranged in layers, all molecules in a layer have their directors tilted, with some random deviations, to the plane of the layer. Also in the smetic A phase the molecules are arranged in layers but now the directors are, with random deviations, perpendicular to the plane of the layer. Unlike in the two smectic phases the molecules in the nematic phase are ordered in only one dimension. The molecules can move in all directions but their directors are, with random deviations, parallel to the average director of the LC.

Liquid crystals are organic compounds and in most cases the molecules are shaped like rods. Rod-shaped molecules are also called calamitic. Liquid crystals with disc- or lath-like molecules also exist but the rod shaped molecules are the most common and they are the type used in LCDs. More than 20,000 calamatic compounds are known [3][5]. The rod-like molecules have a head and a tail. However it is not important which end is head and which is the tail instead it is more common to talk about the director of the
molecule[3]. The director is parallel to the body of the molecule and it does not
matter if it points from the head or tail of the molecule. Molecules of calamatic
compounds have different optical characteristics depending on the direction of
the incoming light. If the incoming light oscillates perpendicular to the director
the liquid crystal will have a smaller refractive index than if the light is parallel
to the director. The first refractive index is called ordinary, \( n_0 \) or \( n_\perp \), and the
latter extraordinary, \( n_e \) or \( n_\parallel \). The birefringence \( \Delta n \) is the difference between
the extraordinary and ordinary indices. That is
\[
\Delta n = n_e - n_0. \tag{Eq 2.1}
\]
The refractive indices depend on the wavelength of light. Normally \( n_0 \) and \( n_e \)
are known for a specific wavelength, typically 589.3 nm. The values for \( \Delta n \) lie
in the range \( \Delta n \in [0.04, 0.45] \) [3] for most liquid crystal materials.

### 2.3 Basic operation of a LCD

A Liquid Crystal Display (LCD) consists of two glass substrates that form a
cell. The two glass substrates are glued together along the edges, except one
small hole into which the liquid crystal can be filled. A typical cell is very thin,
usually 2 – 15 \( \mu \)m, and to achieve the desired cell gap between the glass
substrates throughout the cell, it is filled with spacers see figure 2.5. The
spacers are particles with a highly precise size and are so small that they
individually are invisible to the human eye.

![Figure 2.5 Spacers are placed between the two glass substrates to ensure that
the right cell gap is maintained. Figure source [4].](image)

The insides of the glass plates are covered with an alignment layer. This layer
is made of organic material such as polyamide. The alignment layers are
rubbed in a way that generates grooves. Since the liquid crystals used are rod
shaped they are anchored into the grooves and arranged parallel to them, see
figure 2.6. The grooves on the two glass substrates however are perpendicular
to each other, which forces the LC-molecules to perform a helix with a twist
angle of \( \beta=90^\circ \) between the substrates, see figure 2.7.
Chapter 2, Background

Figure 2.6 The LC molecules arrange themselves into the grooves of the alignment layer. Figure source [4].

Figure 2.7 The alignment layers on the two different glass substrates are perpendicular to each other which forces the LC molecules to form a helix. Figure source [4].

On the outside of the glass substrates polarizers are attached, their orientation are parallel with the orientation of the alignment layer on respective glass substrate. This means that the two polarizers will be perpendicular to each other. As mentioned earlier virtually no light can pass two crossed polarizers, but due to the birefringence in the LC-material it can. The components of the electric field vector of the light that pass the directors of the LC-molecules parallel and perpendicular travel with different speeds, which depend on wavelength. They superimpose along a path between the two glass substrates and change their polarization. If the distance d between the substrates satisfies

\[ d = \frac{\sqrt{3} \lambda}{2 \Delta n} \]  

(Eq 2.2)

where \( \lambda \) is the wavelength of light and \( \Delta n \) is the dispersion of birefringence of the LC-material then the incoming light will have its polarization rotated by 90° and thus can pass the second polarizer [3]. In this case the LC-cell appears to be white (or blank) see figure 2.8.
Figure 2.8 The incoming light beam will be polarized by the first polarizer. Due to the birefringence in the LC material the beam will be twisted 90° and thus it can pass the second polariser that is perpendicular to the first one. The LCD appears white. Figure source [4].

By applying a voltage across the cell it is possible to hinder the light to pass through and the cell appears to be black. The reason why the light can not pass is that when a strong enough voltage (>2V) is applied, the directors of the LC-molecules arrange themselves parallel to the electric field vector. Thus the helix structure disappears and the polarization of the light will no longer be rotated and then it can not pass the second polarizer, see figure 2.9.

Figure 2.9 The applied voltage destroys the helix structure, the light beam will no longer be twisted and thus it can not pass the second polarizer. The LCD appears black. Figure source [4].

The light source used in LCDs can vary. There are basically two different types of LCDs, the transmissive and the reflective. In the case of a transmissive LCD a built in light source shines through the LCD as in for example flat computer screens. A reflective LCD uses an external light source such as a lamp or the sun light. On the back of a reflective LDC a reflector is placed, which reflects the light back through the cell. Reflective LCDs are used for example in wrist watches and sun powered calculators.

The LCD described in this chapter is called a twisted nematic LCD (TN LCD) since it uses nematic (rod-like) LC-molecules and has a 90° twist. So called super twisted nematic (STN LCD) are also used, they use a twist that is greater than 90°, normally 270°. To achieve a twist greater than 90° the LC has to be
doped with chemical compounds that are not symmetrical. Then the molecules can not be parallel and a helix is formed due to asymmetry. If, as in the LCD described, the cell appears white when no voltage is applied it is called normally white mode. It is also possible to make LCDs in normally black mode, in that case the cell appears black if no voltage is applied and white if there is. To make a normally black LCD one simply puts the two polarizers parallel to each other. Then no light can pass if no voltage is applied since polarization of the light will have been twisted by the time it reaches the far side of the cell.

2.4 Theoretical Background

To produce a LCD with a perfect image quality it is, as mentioned earlier, required to get the following LC cell parameters right: cell gap, twist angle, and the dispersion of birefringence. A number of methods to find the unknown parameters have been proposed. Bryneel et al [9] for instance describe a method for determining the cell gap based on the reflection of light. However only in a few of these methods is it possible to measure several parameters simultaneously. Methods that can measure all parameters at once are especially attractive since other methods often require that the rest of the parameters are known in advance. Even fewer, if any, of these methods have been realised from theory into a working system. The method used in this paper is based on the theories presented by Valyukh et al [6], [7], [8].

The optical arrangement and measurement procedures presented here applies to filled transmissive LC cells. A filled LC cell it is a LC cell that is filled with the liquid crystal (there exists theories for how to calculate cell gap on empty LC cells). For measuring reflective ones there is a slight different set-up and the procedure is somewhat different, but the idea is more or less the same.

![Figure 2.10 Optical arrangement of the measurement system.](image-url)
The measurement system consists of a light source, two polarizers and a computer controlled spectrometer, see figure 2.10. The LC cell that is to be measured is placed between the two polarizers. Before the measurement actually starts the spectrometer analyses the intensity of the light source $I_0(\lambda)$, for different wavelengths (typically 340 – 780 nm). Thus neither the polarizers or the LC cell is present during the first step of the analysis. Next the spectrometer analyses the intensity of the light that passes through the two polarizers and the LC cell, $I_s(\lambda)$. The transmittance is the ratio between the intensity of the light that can pass though the LC cell and the intensity of light without cell. It calculated as:

$$T(\lambda) = \frac{I_s(\lambda)}{I_0(\lambda)} \quad \text{(Eq 2.3)}$$

The characteristics of function $T(\lambda)$ are dependent on four variables: cell-gap, twist angle, birefringence, and the orientation of the cell. The function will fluctuate with the wavelength and it will have a theoretical maximum of one, or unity, when all light of that wavelength passes through the cell. It will also have a theoretical minimum of zero, when no light of that wavelength can pass the cell, see figure 2.11. This procedure is then repeated a chosen number of times but between the separate measurements the cell is rotated an arbitrary angle. The result is a collection of functions $T_i(\lambda) - T(\lambda)$, from which the so called characteristic function is calculated. The characteristic function is built in the following way of the measured transmittances of the cell:

$$S'(\lambda) = \sum_{i=1}^{K} \sum_{j=i+1}^{K} \left| T_i(\lambda) - T_j(\lambda) \right|^2 \quad \text{(Eq 2.4)}$$

where $K$ is the number of measurements and $T_i(\lambda)$, $T_j(\lambda)$ are measured spectral transmittances. One might say that $S'(\lambda)$ is the difference between all the measurements. $S'(\lambda)$ reaches its minimum (zero in ideal case) under the following condition:

$$d\Delta n = \lambda_{\text{min}} \sqrt{N^2 - \left(\frac{\varphi}{\pi}\right)^2} \quad \text{(Eq 2.5)}$$

where $d\Delta n$ is the optical retardation, $\lambda_{\text{min}}$ is the wavelength where the characteristic function has its minimum, $N$ is an integer number, and $\varphi$ is the twist angle.

\[\text{Figure 2.11 An example of how a transmittance graph might look.}\]
The characteristic function can be described by the following analytical expression:

\[ S'(\lambda) = A \sin^{2\alpha} X \left( 1 - \frac{\varphi^2}{X^2} \right) \]  

(Eq 2.6)

where \( A \) is a positive coefficient (the more measurements the larger the \( A \)-value) and

\[ X = \sqrt{\varphi^2 + \left( \frac{\pi d \Delta n}{\lambda_{\text{max}}} \right)^2} \]  

(Eq 2.7)

The wavelengths of maxima of the characteristic function \((\lambda_{\text{max}})\) satisfy the equation:

\[ \cot X = \frac{\varphi^2}{\varphi^2 X - X^3} \]  

(Eq 2.8)

To find the unknown desired parameters the idea is to use the measured data that describes the characteristic function (Eq 2.4) and use them as a key. The parameters \( A, \alpha, \Delta n \) and \( \varphi \) of the analytical expression of the characteristic function (Eq 2.6) are then varied until its graph has the smallest possible difference compared to the data key.
Chapter 3

Fitting the graphs

This chapter explains the method and algorithm that has been used to fit the analytical algorithm with the measured data.

With each measurement of the LC-cell, data is read from the spectrometer. The data from the spectrometer are given as pairs of floating point numbers. One part of the pair represents the wavelength in nanometers and the other the intensity of light that has been transmitted through the LC-cell at that particular wavelength compared to without cell. Each measurement consists of an array with approximately 2 000 such pairs. The measurements are stored in a two-dimensional array (here called mA). From the different measurements (at least two is necessary) the characteristic function (Eq 2.3) is calculated. The result will be a one-dimensional array of pairs. The characteristic function is calculated in the following way, see figure 3.1.

\begin{verbatim}
FOR l=0 TO the number of measurement points
  s=0
  FOR i=1 TO the number of measurements
    FOR j=i TO the number of measurements
      s = s + (mA[i][l] - mA[i][j])^2
    characteristicFunction[l] = s

Figure 3.1 Pseudo code for calculating the characteristic function
\end{verbatim}

The data in the array that represents the characteristic function needs to be fitted against its analytical expression (Eq 2.6). This is done with a modified version of the Nelder-Mead Simplex algorithm.

3.1 The Nelder-Mead Simplex Algorithm

An algorithm for unconstrained optimisation that has been used to solve parameter estimation and other problems since it was proposed by Nelder and Mead in 1965 [2] is the Nelder-Mead Simplex algorithm. The algorithm works with simplexes. In two dimensions, with two unknown parameters, a simplex is a triangle and in three dimensions it is a tetrahedron. In n-dimensions a simplex is a geometrical figure with n+1 vertices and an edge between every two vertices.

The algorithm starts by calculating the function values in each of the vertices. The vertices are then sorted from best value (smallest function value) to worst value (largest function value) x_0, ..., x_n. The principle is then to change the worst vertex to a better one. Then the vertices are sorted again and the procedure repeated. The key point is how to choose the new vertex.
With every iteration the algorithm tests up to four new points along a certain line. The line can be represented by \( \bar{x} + \xi (\bar{x} - x_n) \), \( \xi \in \mathbb{R} \), where \( \bar{x} \) is the midpoint of the vertices \( x_0, \ldots x_{n-1} \). The four values denoted by \( \xi \) are called \( \alpha, \pm \beta, \gamma \) and one or more of these values are considered at each iteration. They have to satisfy

\[
0 < \beta < 1, \quad 0 < \alpha < \gamma, \text{ where } \gamma > 1 \tag{Eq 3.1}
\]

Typical values for these parameters are \( \alpha = 1, \beta = 0.5, \gamma = 2 \) [10]. With these values the point calculated with \( \alpha \) will yield a reflection of the worst vertex called \( x_r \), \( \gamma \) yields an extended reflection of the worst vertex called \( x_e \), \( \beta \) and \( -\beta \) yields outer and inner contraction \( x_c \) and \( x_{cc} \), outer contraction means the point between the reflection point and the midpoint and inner contraction is the reflection of the outer contraction point see figure 3.2.

**Figure 3.2** Shows the triangle \( x_1x_2x_3 \) where \( x_3 \) is the worst vertex. \( \bar{x} \) is the midpoint of the vertices \( x_1 \) and \( x_2 \), \( x_r \) is a reflection of the worst vertex \( x_3 \), \( x_e \) is a further extension of \( x_r \) by the same distance.

First the algorithm calculates the reflected point \( x_r \) and if it is smaller than the worst index \( x_n \) the extended point \( x_e \) is calculated. If \( x_e \) is smaller than \( x_r \) then \( x_n \) is exchanged for \( x_e \), if not then \( x_n \) is exchanged for \( x_r \). However if \( x_e \) is not smaller than \( x_n \) then \( x_c \) and \( x_{cc} \) are calculated. The smallest of these values are compared to \( x_n \) and if it is smaller then \( x_n \) is exchanged for that point. If no change has taken place so far into the iteration then the algorithm shrinks the simplex. The shrink replaces each \( x_i \) by \( x_0 + \sigma (x_i - x_0) \) for \( i=1, \ldots n \), where \( 0 < \sigma < 1 \). That is all vertices except the best are moved closer to the best one. As a last step the vertices are again sorted from best to worst. The pseudo code for the Nelder–Mead is given in figure 3.3.
Choose $\alpha, \beta, \sigma, \gamma$
Choose starting vertices for the simplex
Calculate function values for the vertices
REPEAT
  Sort vertices ascending
  calculate $x_r$
  IF $x_r < x_n$ THEN
    calculate $x_e$
    IF $x_e < x_r$ THEN
      $x_n := x_e$
    ELSE
      $x_n := x_r$
  ELSE
    calculate $x_c$
    calculate $x_{cc}$
    IF $(x_c OR x_{cc}) < x_n$ THEN
      IF $x_c < x_{cc}$ THEN
        $x_n := x_c$
      ELSE
        $x_n := x_{cc}$
    ELSE
      shrink simplex
  END
UNTIL end condition is satisfied

Figure 3.3 Pseudo code for the Nelder-Mead simplex algorithm.

Typically the end condition is satisfied when one of two conditions are true. The first one (the one you are hoping for) is that the difference between the edges in the simplex are smaller than a certain tolerance number. If this happens it means that a minima is found and that the precision is acceptable. The other condition is that the number of loops that has been performed exceeds a maximum number. In this case the function does not converge, at least not under the specific parameters. The reason for this can be a number of things, the function might not have a local minima, the choice of start edges might bee bad or the maximum number of loops might bee to low for the algorithm to reach the minima.

3.1.1 Modification of Nelder-Mead

The Nelder-Mead algorithm is intended to find a local minima in a function such as $f(x, y) = x^2 - 4x + y^2 - y - xy$. In this case however the algorithm is used to fit a number of measurement points to an analytical expression namely (Eq 2.6). Every edge in the simplex represents an unknown value (in this case four: the cell gap $d$, the twist angle $\phi$, the birefringence $\Delta n$ and the coefficient $A$). To calculate the value of one edge the procedure is as follows. For each wavelength that the spectrometer has measured a value is calculated using the expression (Eq 2.6) and the values from the specific edge. The difference between that value and the actual value that the spectrometer measured is noted. This procedure is repeated for each wavelength and all differences are added together to a sum. It is this sum that is the value of the edge. If the sum is low it means that the difference between the analytical expression and the measured data also is small.

However the Nelder-Mead algorithm has been shown not to converge or to converge to nonsolutions on certain problems, especially when the numbers of dimensions are greater than two. This has been shown by Price et al. [10]. In
this case the number of unknown parameters is four and unfortunately, when
used on this problem, the algorithm often converges to a non solution. The
problem occurs if the reflected point \( x_e \) is smaller than the worst point \( x_n \)
and the extended point \( x_r \) is smaller than the reflected point and the best point
\( x_i \) (lines 7-10 in the pseudo code in figure 3.3). If this is the case then the
desired point lies further away in the direction of the vector \( \overrightarrow{x_rx_e} \) and the
algorithm will, under certain circumstances, never reach it. To help prevent this
problem a slight modification of the algorithm can be done. If the extended
point is smaller than the best point then another more extended point is
calculated. This procedure is repeated until the new extended point no longer is
smaller than the last extended point. The smallest of the new points is then
exchanged for the worst point in the collection of vertices. These changes add
new rows between row 9 and 10 in the modified pseudocode, the changes are
shown in figure 3.4.

\[
\begin{align*}
7 & \text{ IF } x_r < x_n \text{ THEN} \\
8 & \quad \text{ calculate } x_e \\
9 & \quad \text{ IF } x_e < x_r \text{ THEN} \\
9b & \quad \text{ REPEAT} \\
9c & \quad \text{ calculate new } x_{ee} \\
9d & \quad \text{ IF } x_{ee} < x_e \text{ THEN} \\
9e & \quad x_e := x_{ee} \\
9f & \quad \text{ UNTIL } x_{ee} > x_e \\
10 & \quad x_n := x_e \\
11 & \quad \text{ ELSE} \\
12 & \quad x_n := x_r
\end{align*}
\]

Figure 3.4 The modified pseudo code for the Nelder-Mead simplex algorithm.

### 3.1.2 Choosing start points

For the Nelder-Mead algorithm to work properly it is necessary to have good
starting points. As mentioned above for a system with \( n \) unknown variables it is
necessary to have \( n+1 \) starting points or vertices. Lagarias et al [1] proposes
that the starting points should be chosen in the following way. One point
should be an estimated point, the better the estimation the greater chance for
success, and the other \( n \) points should be orthogonal to each other.

To find acceptable values for the estimated point the system randomly chooses
a number of points and then picks the point with the lowest value (the best
point). This procedure to guess a point is a rather inefficient way to find a good
estimation and there are ways to improve it. The system wants to find four
unknown variables namely the cell gap \( d \), the twist angle \( \varphi \), the birefringence
\( \Delta n \) and the coefficient \( A \). Of these the coefficient \( A \) is the easiest to make an
estimation of. In theory \( A \) can be any positive number but by analysing the data
one can make an estimation of the value of \( A \). As stated earlier, \( A \) is dependent
on the number of measurements done -the more measurements the bigger the \( A \)
value. If one examines the characteristic function (Eq 2.6) one can see that it is
a sine wave where every local maximum is no bigger than the maximum
preceding it and the height of these maximums are dependent on \( A \). This means
that the coefficient \( A \) has a value that is not smaller than the global maximum
of the characteristic function. In most cases the value of \( A \) lies between the
value of the maximum of the characteristic function and 1.05 times that value.
This narrows the range of numbers to guess from when it comes to choose an
acceptable value of A. The remaining three variables d, φ and Δn are the ones that the user are interested to know the value of. The system is intended to measure LC-cells with the following variable span: d 0.2…20nm, φ 0…360°, Δn –0.01…0.01. However the user is able to enter a narrower range for each of these parameters. If for instance the user uses the system to check whether the cell gap of a cell actually is 8nm as expected the range can be entered as 7…9nm since it is very unlikely that the gap should be outside that range if the aim was to make it 8nm.

The easiest way to make n vectors of n dimensions orthogonal to each other is of course to set all parameters but one in the vector to zero. The one that is not zero should of course not be the same one in all vectors. The size of the non-zero parameter should match the size of the unknown variable that it represents. If for example a variable is expected to vary somewhere between 5 and 15 a good choice might be 10 rather than 1000 or 0.001.

### 3.2 Non Ideal Hardware

In a perfect world what has been discussed to this point should be sufficient to calculate the desired parameters. However it is not a perfect world and the data that is read from the spectrometer is not ideal and contains irregularities that cause problems. One problem is that the data, when plotted in a graph, is not as smooth as one could wish, it contains noise. This noise makes the data irregular which makes it harder for the system to find the right values to the desired parameters. Since the characteristic function (Eq. 2.4) is a sum of a number of measurements the impact of random noise can be lessened by making more measurements. If the number of measurements is big enough the random noise of the individual measurements will work against each other and thus make the noise impact of the characteristic function lessened. If this is not enough there are methods for smoothing that can be used. Another problem that is a bit more serious is that the intensity that the spectrometer measures seems to vary with the measured frequency. The spectrometer measures the differences in intensity between the amount of light that passes through the LC-cell compared to without cell according to equation 2.3. In theory this gives a maximum of one or unity when the intensity of the light that passes through the LC-cell is the same as without cell. A line that describes the unity should have the equation y = 1. In reality however it shows that this unity line is not a perfect one, in fact it might not even have to be a straight line it can be a parabola

\[ y = ax^2 + bx + c. \tag{Eq 3.2} \]

The differences are described in figure 3.2.

For the system to work properly it is desirable that it can detect this non ideal unity line. One way to approach the problem could be to just increase the number of unknown parameters in the original problem. That is, add a, b, and c from equation 3.2 to the already unknown parameters. That would give seven unknown parameters in total. Having in mind the problems that four unknown parameters caused trying to find a proper starting point and to get the algorithm to converge one can easily see that seven unknown parameters are going to need a somewhat different approach.
3.2.1 Compensating for Non Ideal Hardware

One way to deal with the problem is to first use the method described earlier and just ignore the fact that the circumstances are not ideal. The results from such a calculation are not good enough for final results but they can be used as start values for different methods.

The transmittance (Eq 2.3) can be described analytically as:
\[
T(\lambda) = \cos^2(\varphi + p) + \sin^2\left(\varphi \sqrt{1 + u^2}\right) \sin(2(\varphi - \alpha + p)) \sin(2\alpha) \quad \text{(Eq 3.3)}
\]
\[
+ \frac{\sin(2\varphi \sqrt{1 + u^2}) \sin^2(2(\varphi + p))}{2\sqrt{1 + u^2}}
\]
\[
- \frac{\sin^3\left(\varphi \sqrt{1 + u^2}\right)}{(1 + u^2) \cos(2(\varphi - \alpha + p)) \cos(2\alpha)}
\]

where
\[
u = \frac{d}{\lambda \varphi (l_1 + \Delta n(\lambda^2 - l_o^2 - l_0^4))} \quad \text{(Eq 3.4)}
\]

and \(\alpha\) is the angle of the LC-cell compared to the spectrometer, \(\lambda\) is the wavelength, \(p\) is a positive constant (0 \(\leq\) \(p\) \(\leq\) \(\pi\)) \(l_o\) and \(l_1\) are constants that are dependent on the specific liquid crystal used. The expression (Eq 3.3) describes the characteristics of the individual measurements of the cell. What is different between the measurements is the angle \(\alpha\). \(\alpha\) is the orientation of the cell compared to the spectrometer, and it is different with every measurement. Since the measurement process is supposed to be as easy as possible to perform, it does not matter how much the LC-cell is rotated between the measurements, so the values of \(\alpha\) will be unknown.

If the \(\alpha\) values of the measurements were known, equation 3.3 could be used for detecting the non ideal unity line. However the \(\alpha\) values can be approximated with help of the values calculated first. If those values are assumed to be the right values then \(\alpha\) is the only unknown parameter left. This makes it straightforward to calculate, for example a golden selection search could be used.
Once $\alpha$ is known, equation 3.3 divided with equation 3.2 could be used to find the unity parabola. This gives again a problem with seven unknown parameters, but four of them are not completely unknown since they have been calculated before. The remaining three are $a$, $b$, and $c$ from equation 3.2. This means that it is possible to use the same technique as before namely the Nelder Mead algorithm to find the answer. In this stage the main concern is not to find the correct values of the three original parameters ($d$, $\varphi$, and $\Delta n$) but to identify $a$, $b$ and $c$ from equation 3.2. To force the algorithm to concentrate on $a$, $b$, and $c$ the others can be weighted. That means that a change in $\alpha$, $d$, $\varphi$, and $\Delta n$ have a greater impact than a change in $a$, $b$, and $c$, this way the algorithm can be somewhat controlled. The weight can be performed by multiplying the difference between the start value of that variable and its new value with a constant. The size of the constant depends on the size of the variable and how good the start value is. A large value of the constant indicates that the start value is rather close to the true value and does not need much change.

When the equation of the unity parabola is known, or at least an approximation, it can be used when measuring the LC-cell again. The measurements are now divided with the parabola and as a result the new unity parabola will be much closer to a unity line. This procedure can of course be repeated until adequate results have been achieved. To save time and effort the data from the measurements of the first round can be saved and used again through the entire process, the data will then simply be divided by the new parabola and no new measurements need to be done.
Chapter 4

Results

In this chapter the results of the system and the accuracy of the calculated parameters are discussed.

A problem that immediately becomes clear when one tries to evaluate how accurate this measurement system can measure the unknown parameters is that, since the parameters are just unknown, it is hard to know the right answer. If the right values to the wanted parameters is not known then how is it possible to know if the values that the system calculates are right? When a LCD-cell is produced one might have as a goal to make the cell gap for example 7.5nm and the twist angle 90°. If the system then gives the answer; cell gap 14nm and twist angle 70° then one can for sure see that the system is not working. If, on the other hand the system answers; cell gap 7.65nm and twist angle 88.5° then it is very difficult to say if the system is right and the LCD-cell has in fact those parameters or if the accuracy of the system allows for such differences.

4.1 An Ideal Case

The equation for transmittance (Eq 2.3) can, as said in chapter 2, be described analytically as equation 3.3. This can be used in a computer program to simulate the data that is read from the spectrometer, see figure 4.1. This data is then treated just as if it were the real data and the characteristic function is built in the usual way using the equation 2.4, see figure 4.2. By doing this one can know the exact values of the desired parameters, which is a condition for making an evaluation of the system’s usefulness. Of course using this method will simulate an ideal case without noise and other disturbances that can interfere with the measurements.
Figure 4.1 Three simulated measurements on a LDC with parameters $d$: 7.5nm $\varphi$: 45° and $\Delta n$: 0.004 measured at different cell orientations.

Under these ideal conditions the system finds the answers to the parameters with good accuracy. Table 4.1 shows the results. Although the calculated values do not differ much from the real values the characteristic function produced by the analytical expression (Eq 2.6) and the calculated results is not identical to the characteristic function built by the differences of the measurements according to (Eq 2.4), this can be seen in figure 4.3.

Table 4.1 Differences between the actual and calculated values in an ideal simulation.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell gap</strong></td>
<td>7.5</td>
<td>7.50065</td>
</tr>
<tr>
<td><strong>Twist angle</strong></td>
<td>45</td>
<td>45.0076</td>
</tr>
<tr>
<td><strong>$\Delta n$</strong></td>
<td>0.004</td>
<td>0.0039997</td>
</tr>
</tbody>
</table>
Chapter 4, Results

Figure 4.2 The characteristic function shows the differences between the different measurements. Where the measurements intersect the characteristic function has its minimum.

Figure 4.3 The lighter line shows the characteristic function calculated using equation 2.4. The darker line shows the characteristic function drawn using the calculated parameter values and the analytic expression of the characteristic function (Eq 2.6). The Graph shows a close up of the first maximum of the characteristic function also shown in Figure 4.2.

4.2 Random noise error
As mentioned above one cannot expect to get as ideal measurements as shown in figure 4.1. In reality the graphs will not be as smooth and exact as in the figure. They will be disturbed by noise. It is essential that the system can cope
with noise since it otherwise would not be very useful when used in reality. To simulate noise the data produced by Eq 3.3 can be multiplied with a random number. Figure 4.4 shows an example of a simulated measurement with noise.

![Figure 4.4](image)

*Figure 4.4 Three simulated measurements with the same parameters as in figure 4.1 but with random noise.*

The noise in the individual measurements will of course also affect the appearance of the characteristic function. But since the noise is random the system finds a solution to this problem too, see figure 4.5.

![Figure 4.5](image)

*Figure 4.5 The characteristic function produced from three noisy measurements will itself contain noise. The darker line represents the calculated solution.*

However the noise has some impact on the results. Table 4.2 shows the calculated results.
Table 4.2 Difference between actual and calculated values in a simulation with random noise based on three measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.492</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>46.03</td>
</tr>
<tr>
<td>Δn</td>
<td>0.004</td>
<td>0.00397</td>
</tr>
</tbody>
</table>

If the results of table 4.1 are compared to the results of table 4.2 one can see that the values are slightly less accurate under the latter conditions. Especially the twist angle is inaccurate. If the number of measurements are increased then the noise from the individual measurements will not have the same impact on the characteristic function as in the case when only a few measurements are done. Figure 4.6 shows the characteristic function based on 100 simulated measurements with noise.

![Figure 4.6](image)

*Figure 4.6 Characteristic function produced from 100 simulated measurements. The relative level of noise is smaller then in the case of fewer measurements. The dark line represents the calculated solution.*

Note that the amplitude of the curve is far greater then in the previous example with three measurements. This greater amplitude has itself no impact on the values of the parameters that are of interest for the user. The only parameter that is affected is the coefficient A that will be significantly larger, approximately 1200 rather than 1.5. What is of interest however is that the curve is smoother than in the previous example, meaning that the values can be calculated with better accuracy as can be seen in table 4.3. Especially the value of the twist angle has been improved, however it is still the parameter where the calculated result varies the most from the correct value.
Table 4.3 Differences between the actual and calculated values in a simulation with random noise based on 100 measurements.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.502</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>45.13</td>
</tr>
<tr>
<td>( \Delta n )</td>
<td>0.004</td>
<td>0.00398</td>
</tr>
</tbody>
</table>

### 4.3 Wavelength dependent error

What has been shown so far is that the system works satisfactory well under ideal conditions. Even in the case when data is corrupted with random noise it works. If the noise is to strong for a reliable calculation with say three to four measurements it often helps if the number of measurements is increased. As pointed out in earlier chapters, random noise is not the only difference from an ideal case. The spectrometer will in many cases induce an error in the measurements that is dependent on the wavelength and thus it is not random. This can be described as if the unity line (at the wavelength where the graph touches the unity line the intensity of the light passing through the LC-cell is the same as without cell) were exchanged for a unity parabola according to equation 3.2. Figure 4.7 shows how three measurements would look if the unity line were represented by the equation

\[
y = 1 + 0.3x - 0.5x^2
\]  

(Eq 4.1)

When calculating the results using that data of course the results will not be as accurate as with a true unity line as can be seen in table 4.4.

*Figure 4.7 The diagonal crosses represents a non ideal unity line with the equation \( y = 1 + 0.3x - 0.5x^2 \).*

Figure 4.8 shows that the match between the characteristic function built from the simulated data measurements and the calculated solution is rather poor.
Figure 4.8 The match between the calculated and the built characteristic functions are quite poor when the unity line is not ideal.

The method for calculating the unity line that was described in chapter 3 can be used. In table 4.4 the result of the unity line calculation can be seen (the unity line is represented by \(a, b,\) and \(c\) according to equation 3.2). As one can see the difference between the calculated unity line and the real one is quite substantial, but in the region of interest (between wavelength 300 – 800 nm) the match is rather good which can be seen in figure 4.9.

Table 4.4 The accuracy of the parameters will be less with a non ideal unity line.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.469</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>45.87</td>
</tr>
<tr>
<td>(\Delta n)</td>
<td>0.004</td>
<td>0.0042</td>
</tr>
<tr>
<td>(a)</td>
<td>1</td>
<td>0.98</td>
</tr>
<tr>
<td>(b)</td>
<td>0.3</td>
<td>0.34</td>
</tr>
<tr>
<td>(c)</td>
<td>-0.5</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

The calculated unity line will not effect the accuracy of the results in the first place since the measurements are already done. In order to use the new calculated unity line to get better results another set of measurements must be done. This time the calculated unity line is used to limit the effect of the real one and if the two are similar it will seem as the unity line is in fact a true unity line this can be seen in figure 4.9.
Figure 4.9 Second round of measurements. The diagonal crosses represent the unity line and the crosses the calculated unity line. Since the two matches each other quite good the maximums of the measurements touches the line y=1 as if it was the unity line.

This time the calculated values are more accurate as can be seen in table 4.5. A new calculation of the unity line can be done based on the new values which hopefully improves the unity line further. These steps can be performed again and again until satisfactory results are achieved.

Table 4.5 The accuracy of the parameters are improved somewhat in the second round of measurements.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.501</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>44.95</td>
</tr>
<tr>
<td>An</td>
<td>0.004</td>
<td>0.00399</td>
</tr>
<tr>
<td>a</td>
<td>1</td>
<td>0.99</td>
</tr>
<tr>
<td>b</td>
<td>0.3</td>
<td>0.33</td>
</tr>
<tr>
<td>c</td>
<td>-0.5</td>
<td>-0.53</td>
</tr>
</tbody>
</table>

4.4 Random and Wavelength dependent error

If the system is going to be useful in reality it must of course be able to handle both the random noise error and the wavelength dependent error at the same time. When both these errors are present at the same time of course it will be more difficult for the system to find solutions to the variables with good accuracy. As showed before the impact of the random error can be lessened by
making more measurements, therefore the number of measurements in the following examples are increased to twenty instead of three as before.

The first set of results for cell gap, twist angle and the dispersion of birefringence are, not surprisingly, not very accurate which can be seen in table 4.6.

Table 4.6 When both errors are present the accuracy of the parameters are not very good.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.46</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>46.45</td>
</tr>
<tr>
<td>Δn</td>
<td>0.004</td>
<td>0.00422</td>
</tr>
<tr>
<td>a</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>b</td>
<td>0.3</td>
<td>-0.023</td>
</tr>
<tr>
<td>c</td>
<td>-0.5</td>
<td>-0.26</td>
</tr>
</tbody>
</table>

What might be more surprising is that the values of a, b and c in the unity line equation are even more wrong. The first conclusion of this might be that the system can not handle both errors at the same time. However in this application the area of interest is quite small only the area that corresponds to wavelengths between 300 and 800nm are used. If one looks at the two parabolas in just that area one can see that they are not as different as they seemed when just looking at the numbers, this can be seen in figure 4.10.

Figure 4.10 The diagonal crosses represents the unity line $y = 1 + 0.3x -0.5x^2$ and the crosses represents the calculated unity line $y = 1.1 - 0.023x - 0.26x^2$.

In fact the two lines are similar enough that the results produced in the next step are of considerably better accuracy. Table 4.7 shows the calculated values after the second round and after the third round. After round three the values does not get much better, some rounds show better results and some worse but they all have about the same level of accuracy.
Table 4.7 The calculated values are improved after the first measurement.

<table>
<thead>
<tr>
<th></th>
<th>Real value</th>
<th>Calculated round 2</th>
<th>Calculated round 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell gap</td>
<td>7.5</td>
<td>7.49</td>
<td>7.51</td>
</tr>
<tr>
<td>Twist angle</td>
<td>45</td>
<td>45.5</td>
<td>44.8</td>
</tr>
<tr>
<td>Δn</td>
<td>0.004</td>
<td>0.00396</td>
<td>0.00394</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>0.948</td>
<td>0.938</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>0.471</td>
<td>0.567</td>
</tr>
<tr>
<td>C</td>
<td>-0.5</td>
<td>-0.676</td>
<td>-0.759</td>
</tr>
</tbody>
</table>
Chapter 5

Wrapping up

In this final chapter some ideas about how the system might be improved are discussed. Some thoughts about the results and the future of the system are also presented.

5.1 Discussion

The aim of this thesis project is to suggest and implement a method that can be used in a system for measuring certain parameters in the manufacturing process of LCDs. In the previous chapter the results of the chosen method were shown. The results shown indicate that the chosen method can be used to develop the system in the future. However before it can be used in a commercial product a lot of work remain to be done. The results are based on simulations and no matter how much one tries to emulate the real world, with noise disturbing the measurements and hardware that is not as ideal as one could hope for, it will never give a certain answer to the question of how good it actually works. To really determine the efficiency of the system, measurements on real LC-cells must be done. As mentioned in the previous chapter the problem with that is that it is very hard to know the true value of the parameters since no good measurement systems yet exist. To the question of how that testing and verifying are going to be done in reality no really good answer has been found. Instead a number of proposals on how the system might be improved will be given.

As mentioned in the previous chapter the Nelder-Mead algorithm generally converges faster with fewer parameters and the chance to find a solution increases as well. The same is also true if the start values are better.

There might be a way to eliminate one parameter when dealing with the situation with the non-ideal unity line. To day the system tries to find the parabola that represents the unity line. This means that the unknown unity line adds three extra unknown parameters to the problem. Since the individual measurements themselves are not used to find the desired parameters it would not effect the outcome of the answer if all measurements where multiplied with a constant. Of course the amplitude of the measurements would no longer vary between zero and unity but between zero and the constant. The proportional difference between them would however be the same. In other words the characteristic function would still look the same except that it would have another value of its constant A. As said before, the constant A increases with the number of measurements and it is not interesting to know its value but it has to be calculated in order to calculate the values of the desired parameters. So, if only the constant A is affected by the multiplication of the measurements then the results will be the same with or without the constant multiplication.
This indicates that it is not necessary to find the exact parabola that corresponds to the non ideal unity line, it is sufficient to find a parabola that has the same inclination of its tangent as the tangent of the unity line in the corresponding point along the horizontal axis. Thus it is sufficient to find a corresponding derivative to the unity line. If a parabola is derivated then one of its components is lost and it becomes a line, and thus it is no longer necessary to look for three parameters. The integral of the calculated line is then taken which gives a parabola with an unknown constant. This constant is thought to be zero. The measurements are then normalized with the new parabola in the same way as before but now they vary between zero and an unknown variable. This however will not, as said before, affect the outcome of the results.

As the system is presented in this paper the user specifies ranges in which the unknown parameters are supposed to be. These ranges are used to find a good starting point, the more precise (smaller) the range is the more likely it is that the system finds a good enough starting point. As seen in the results chapter the twist angle is normally the parameter with the worst accuracy, so if it could be calculated in a different way it might impose an improvement. In fact, it is possibly to calculate the twist angle in such a different way. The twist angle can be calculated directly from the measurements instead of from the characteristic function. Two different measurements always intersect at some points. These points are always at the same level of transmitted intensity and all measurements, regardless of the \( \alpha \) angle, will intersect at the same places. The height of these points (that is the level of transmitted intensity) are dependent on the twist angle. If for instance the twist angle is \( 0^\circ \) then the intersection points will have the intensity equal to unity, if the angle is \( 45^\circ \) then the intensity is equal to half unity and if the angle is \( 90^\circ \) then the intensity is equal to zero. This means that it is quite straight forward to implement a search algorithm that finds these points and then calculates the twist angle. Of course, this method will also have problems with noise and non ideal unity. However the user must know in what quarter the twist angle lies since for example a twist angle \( 80^\circ \) would yield the same intensity at the intersection points as one of \( 100^\circ \). It should not however be a big problem to know in what quarter the twist angle lies. If this way to calculate the twist angle is chosen then there are two options. The first option is to eliminate the twist angle from the following calculations and thus the system will have one less unknown parameter which might improve the accuracy. The other option is to use the calculated twist angle as a start value in the following calculations which might render a better start value.

Unfortunately the two improvement techniques presented here do not work together. When using the first technique the value of the unity might be lost and the second technique depends on that the unity is one or at least that it is known.

### 5.2 Future work

It is probably possible to build a commercially useful system for LCD measurement based on the principles presented in this Master’s thesis. However, it is still a long way to go before the system can be released to the market. There are a few things that must be addressed first.
Chapter 5, Wrapping up

The first thing that must be done is to test the accuracy of the system thoroughly under real circumstances, not only simulations. Unfortunately I do not have a good answer to how that can be done. As said earlier it is a problem that the unknown parameters are unknown. If the right values are not known then it is hard to tell how accurate the results really are.

Another thing that must be done is to decide who is going to use the system, and after answering that develop an easy-to-use user interface. The demands on the user interface will of course be very different depending on who is using the system. If the system is going to be used in a production line, testing every LCD, then it must be easy to use and have few parameters to monitor. It might even be a good idea if the system can work on its own without human supervision and only warns when a suspicious error is detected in a LCD. On the other hand, if the system is meant to be used by people in a lab developing and testing new LCD’s there are completely different demands on the user interface. The person using the system must be able to make a lot of adjustments to the setup, but on the other hand the system does not need to work without human supervision.

The hardware must also be adopted to the environment in which the system is thought to operate. If it shall be used in a production line then all the measurement steps must be automated. To measure a LC cell, at least two measurements with the cell rotated in different angles must be done. This rotation and measurement process must be automated in some way to make production line use efficient. In the other case however when the system is used in a lab, there are not as high demands on the hardware as in the production line scenario. In a lab environment it is likely that the number of tests performed will be limited and then it is possible to manually rotate the LC cell and make the measurements.
References


