

Controlling galvanometers for Fourier domain Optical Coherence Tomography for ophthalmology research

Bachelor thesis

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Summary

Optical Coherence Tomography (OCT) is an imaging technique for collecting depth resolved information in human tissue based on an interferometer.

With an imaging depth of between 1 and 2 mm, OCT is only used to investigate (near) surfaces. But with an axial (depth) resolution of between 2 and 10 μm , and a lateral (sideways) resolution between 1 and 100 μm [1][2] the images have a greater resolution than for example a MRI image [3]. In ophthalmology OCT has become a standard tool for non-invasive imaging of the retina and to detect abnormalities or monitor the progress of diseases or treatments.

In order to improve the setup's resolution and lower the costs, an investigation is started at the Academic Medical Centre in Amsterdam, and a complete new OCT setup is built. To deflect the light in order to scan over an area, a duo-galvanometer is used. Also a spectrometer is used to perform measurements. A computer program is written to control the galvanometers and communicate with the spectrometer with the right timing. This is done in National Instruments Labview.

When choosing the motion of the mirrors of the galvanometer, it must be kept in mind that mechanical stress as a result of large acceleration can damage the mirrors. Also a constant scanning speed is desired when the measurements are performed. Therefore, a path with gradual velocity changes is chosen, based on parabolas, with linear sections for the measurements.

Before the mirrors start scanning, the program checks whether the chosen settings can result in a path that exceeds the galvanometers capabilities. The program will only start the scanning if this doesn't cause damage to the mirrors.

The Labview program is written, resulting in a flexible way to control galvanometers.

A user can insert the lateral resolution of the setup, the maximum allowed acceleration of the galvanometers, the borders between which the measurements need to take place and the time between two sequential points of the path.

Future research could improve the communication between the soft- and hardware, and investigate the limits of the capabilities of the galvanometer.

Preface

This thesis is the result of my graduation project for the bachelor Applied Physics at The Hague University in Delft. For a period of 17 weeks I have been working on this project at the Academic Medical Centre (AMC) in Amsterdam, under the supervision of Dirk Faber, Martijn de Bruin and Mitra Almasian. I would like to thank those and all other people who helped me on this internship.

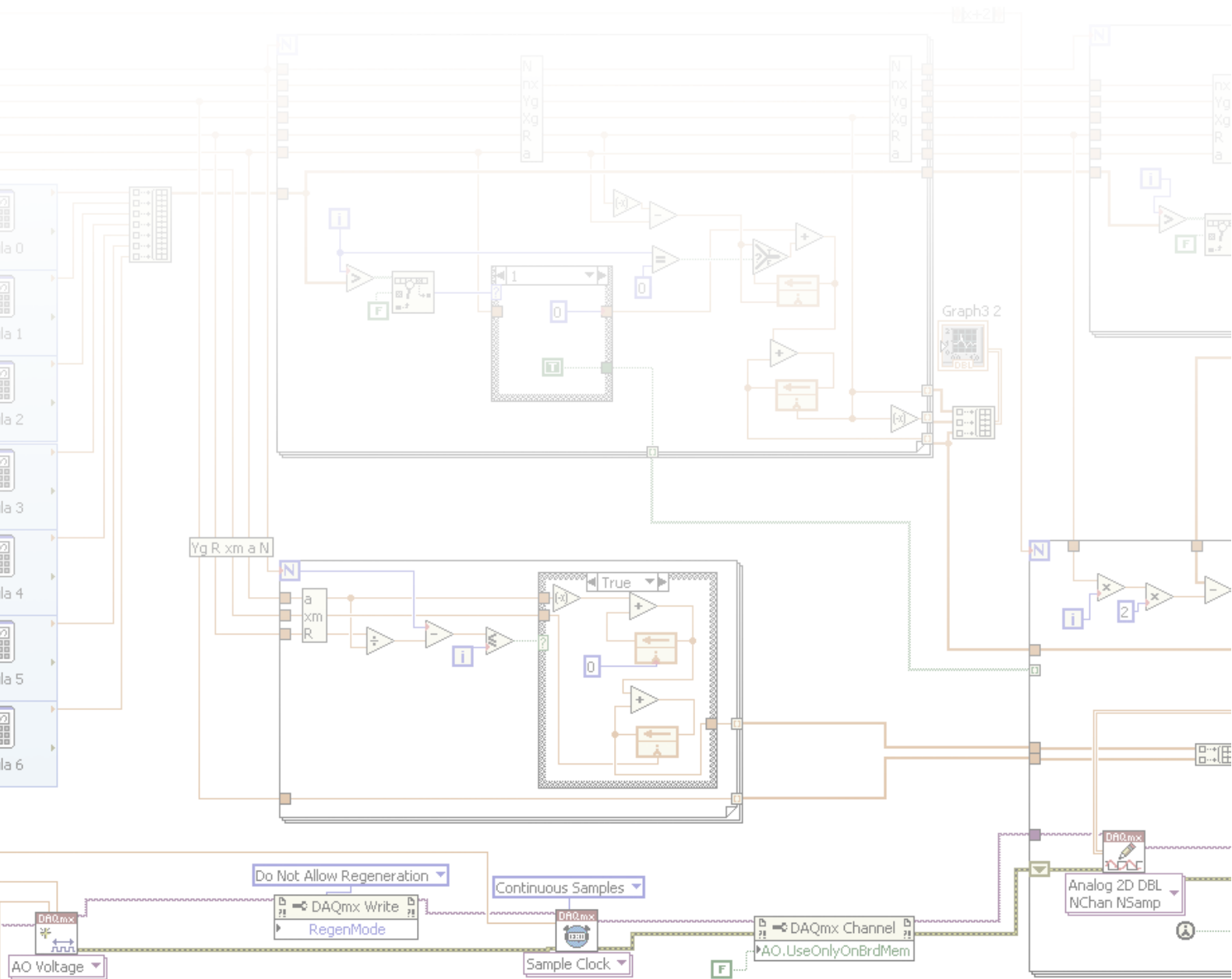


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1. Introduction

Optical Coherence Tomography (OCT) is an imaging technique for collecting depth resolved information in opaque materials. The technique visualizes reflective properties of the material as a result of changes in refractive index by using an interferometer. The setup measures backscatter intensity from a light beam that is directed towards the sample, therefore OCT can be seen as an optical equivalent of ultrasound imaging.

The technique has proven itself useful in several medical disciplines, where images can be created of for example the skin, the bladder or the retina [2].

With an imaging depth of between 1 and 2 mm, OCT is only used to investigate (near) surfaces. But with an axial (depth) resolution of between 2 and 10 μm , and a lateral (sideways) resolution between 1 and 100 μm [1][2] the images have a greater resolution than for example a MRI image[3] (figure 1.1).

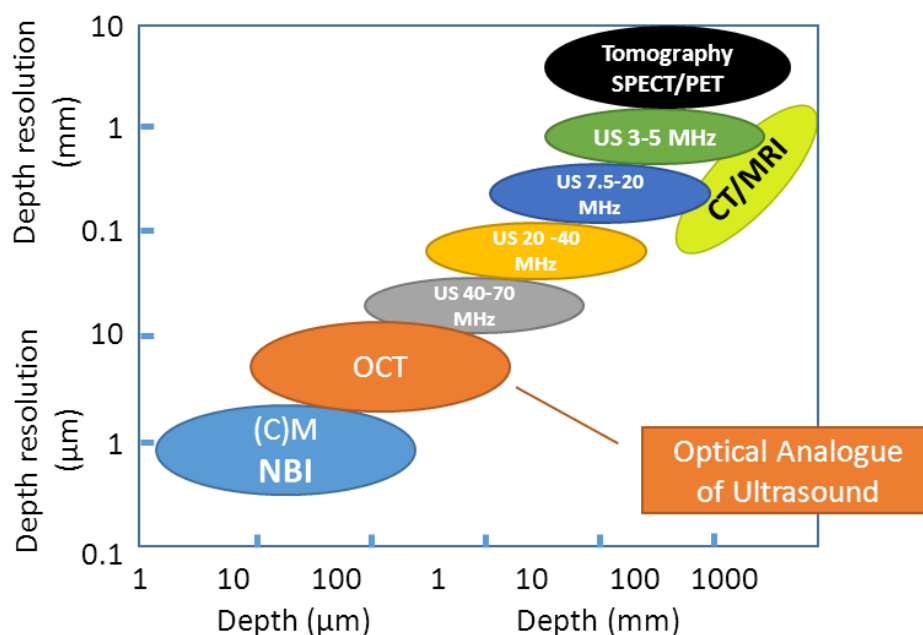


Figure 1.1. The comparison of several imaging techniques, including ultra sound (US), optical coherence tomography (OCT) and confocal microscopy ((C)M)

In ophthalmology OCT has become a standard tool for non-invasive imaging of the retina and to detect abnormalities or monitor the progress of diseases or treatments.

In order to improve the setups resolution and lower the costs, an investigation is started at the Academic Medical Centre in Amsterdam, and a complete new OCT setup is built.

Instead of performing one single measurement on a (tissue) sample, it is desired to scan over the sample to gather information form a bigger region. In order to scan over an area, a duo-galvanometer is used. This is a system that uses two moveable mirrors to deflect the light beam in both x and y direction.

The galvanometers are controlled by a National Instruments Labview computer program. The program controls the movement of the mirrors in order to scan over the exact region of interest, with the desired speed. The program also triggers the measurements, because a proper timing is needed to be able to align all measurements to form a three dimensional image. In order to do this the light beam moves with a constant velocity when it is scanned over the region of interest, to make the distance between every sequential measurement constant, and the position of every single measurement can be calculated.

Also, the acceleration of the galvanometers needs to be limited, to prevent damaging the mirrors.

With these conditions a program can be composed that flexibly can control galvanometer systems for OCT setups. The program can be used to build a flexible setup for research to improve the resolution and lower the cost for retinal OCT imaging in ophthalmology.

2. Optical Coherence Tomography (OCT)

Optical Coherence Tomography (OCT) is an optical imaging technique which measures optical path length differences (OPD) using an interferometer. This way depth resolved information about reflective properties of a material over a certain depth range can be gathered. This can be used to visualize three-dimensional structures in human tissue with an axial resolution between 2 and 1 μm [1][2].

Three types of scans can be distinguished. The data gathered with one measurement, which contains information about the reflective properties at one position on the sample and underneath the surface up to a certain depth, is called an Axial- scan, or an A-scan. By making several A-scans at different neighboring positions, it is possible to construct a cross sectional image of the sample, which is called a B-scan. Again, by making several B-scans in a row, a three dimensional, or volumetric, image of the sample can be constructed, called a C-scan (figure 2.1).

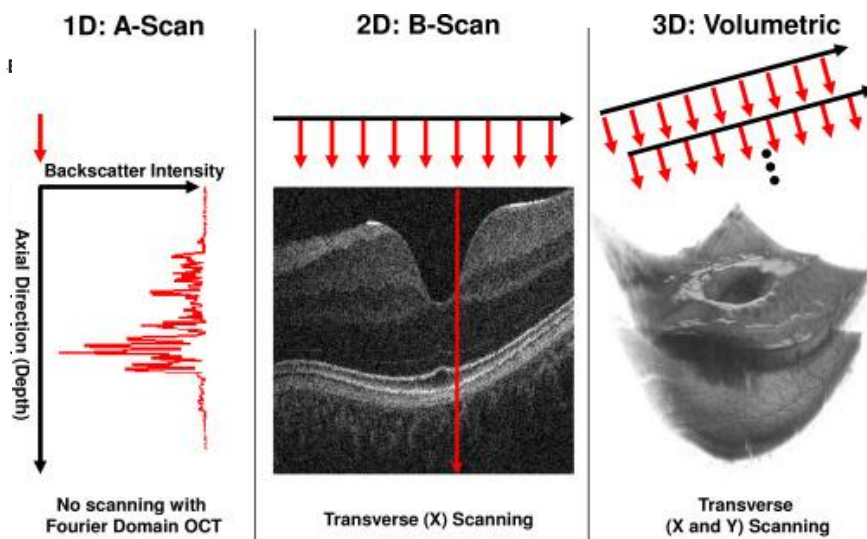


Figure 2.1. Examples of an A-scan, a B-scan and a volumetric scan of a human retina [4]

2.1 Interferometry

OCT is based on an interferometer. An often used interferometer is the Michelson interferometer, figure 2.2.

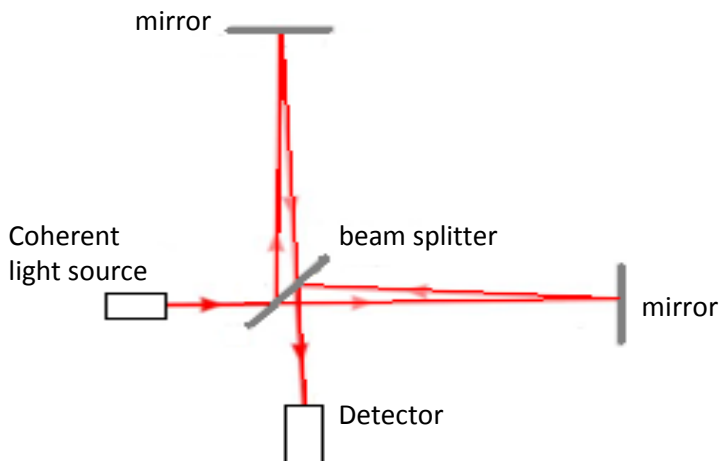


Figure 2.2. A schematic representation of the Michelson interferometer

For an interferometer a light beam from a coherent light source, for example a laser, is split by a beam-splitter over two arms. The beam in one of the arms is reflected by a sample, while the beam in the other arm is reflected by a movable mirror. Next, the beams in the two arms are led back to the same beam-splitter, and are directed to a detector. When the optical path lengths of both arms differ by a whole number of wavelengths, constructive interference will occur. In an ideal situation, with an infinitely small bandwidth source, the following condition is valid.

$$OPD = n\lambda \quad (2.1)$$

with:

OPD	:	The optical path length difference	[m]
λ	:	The wavelength of the radiation	[m]
n	:	A whole number	[-]

When the movable mirror is displaced over quarter of a wavelength, the OPD will change half a wavelength, resulting in destructive interference. When the mirror is displaced half a wavelength, constructive interference will occur again, and this pattern repeats continuously. This means that, using a detector, differences in distance of at least a quarter of a wavelength can be determined, by counting the maxima and minima that drift by while the mirror is moving. This makes the Michelson interferometer capable of measuring distances in the order of magnitude of the wavelength of visible light [5].

2.2 Time domain OCT (TD-OCT)

The first implementation of the Michelson interferometer in OCT was in the time domain. With time domain OCT (TD-OCT), the beam of a broadband light source is split by a beam splitter. One of the resulting beams is reflected back by the reference mirror, while the second beam is reflected by a sample. In the case of a perfect broadband light source, with an infinite bandwidth, the two reflected beams will only interfere constructively when there is no OPD, when they are brought together again by the beam splitter. In the case of a finite bandwidth there will be constructive interference when the OPD is in a region near zero, with a smaller region when the bandwidth is bigger. The size of this region is the resolution of the setup. When the reference arm is extended, reflections of a deeper part of the sample will interfere. By scanning the reference mirror back and forth the reflective properties of the sample can be measured at a range of depths. In this way it is possible to visualize internal structures in the sample.

2.3 Fourier domain OCT (FD-OCT)

In order to accomplish a higher speed of imaging, it is possible to use a different approach of collecting the data. This can be done with the Fourier-domain OCT (FD-OCT). This method also uses a broadband light source, although the interference signal is measured with a spectrometer, instead of a single detector. In the ideal situation of an infinite bandwidth, when a reflection occurs in the sample, the wavelengths that satisfy the condition 2.1 will interfere constructively, and the wavelengths that are in between destructively, forming a cosine shaped signal. The wavenumber of the maxima of the cosine can be calculated by rewriting 2.1.

$$OPD = n \frac{2\pi}{k} \quad \rightarrow \quad k = n \frac{2\pi}{OPD} \quad (2.2)$$

with:

k	:	The wavenumber	[m ⁻¹]
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The cosine can be described by 2.3.

$$I(k) = \cos(OPD \cdot k) \quad (2.3)$$

with:

$I(k)$: The measured intensity as a function of wavenumber [Wm]

Because the light travels back and forth in the reference arm, the OPD is twice the difference in length between the two arms. Therefore,

$$I(k) = \cos(2 \cdot \Delta L \cdot k) \quad (2.4)$$

with:

ΔL : The difference in length between the two arms [m]

The frequency of the cosine signal equals $2 \cdot \Delta L$. For every reflection in the sample, a cosine signal is measured with the spectrometer. By using a Fourier transformation, the separate waveforms can be interpreted to visualize the reflective properties of the sample at a range of depths (figure 2.3).

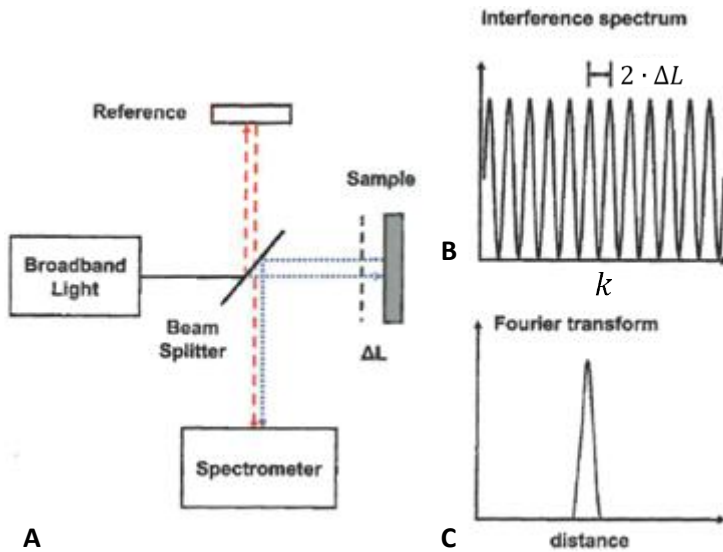


Figure 2.3. A) A schematic representation of the FD-OCT setup B) An example of an interference spectrum as a result of a single reflection C) The Fourier transform of the interference spectrum (adapted from [2])

In order to reach a bigger imaging depth, a variation on the FD-OCT, called the Swept Source OCT (SS-OCT) is used. In this setup one single detector is used, and a light source that has the ability to emit light within a narrow, but moving bandwidth. This means that different wavelengths of light are emitted sequentially. The bandwidth at one moment can be smaller than the resolution of a spectrometer in FD-OCT, which makes that SS-OCT can measure deeper into a sample compared with FD-OCT.

The source often contains moving parts, making it less stable. Also, the sources were initially built for the telecommunications industry, with the consequence that they are not available in all wavelength ranges.

An example of a FD-OCT image can be seen in figure 2.4.

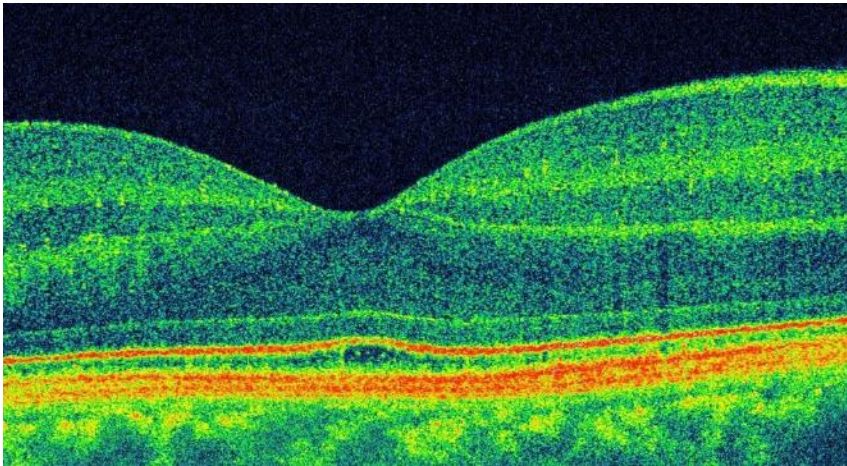


Figure 2.4. An example of a two dimensional FD-OCT image of a human retina [8]

3. Setup

The used setup consist of a fiber based Michelson interferometer to form a Fourier Domain OCT setup (figure 3.1).

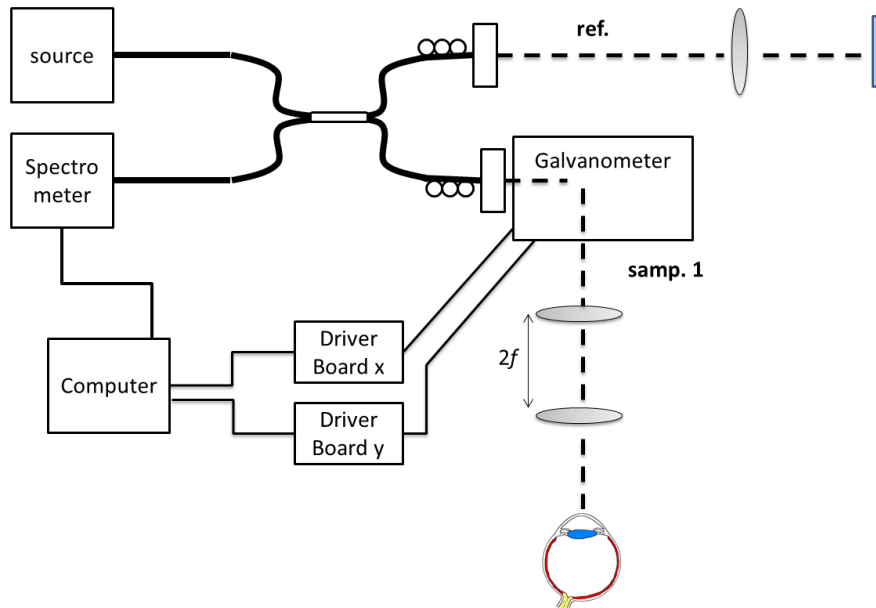


Figure 3.1. A schematic representation of the FD-OCT setup

The source is a Superlum Broadlighter-D type broadband laser source. It uses two laser diodes to create a broadband spectrum with a central wavelength of 848.8 nm and a FWHM of 101.2 nm [6]

The spectrometer is custom made by Bayspec. It has a spectral range from 755 nm to 955 nm, it has 2048 pixels with a pixel size of 10 by 10 μm .

To scan the light beam into the desired direction, a Thorlabs dual axis GVS012 Galvometer is used. It uses two servomotors with mirrors to deflect the light both horizontally and vertically (Figure 3.2). The servomotors are controlled by offering a voltage which represents an angle. The range of the motors are from -20° to 20° . The transmission works with a responsivity of $0.5^\circ/\text{V}$.

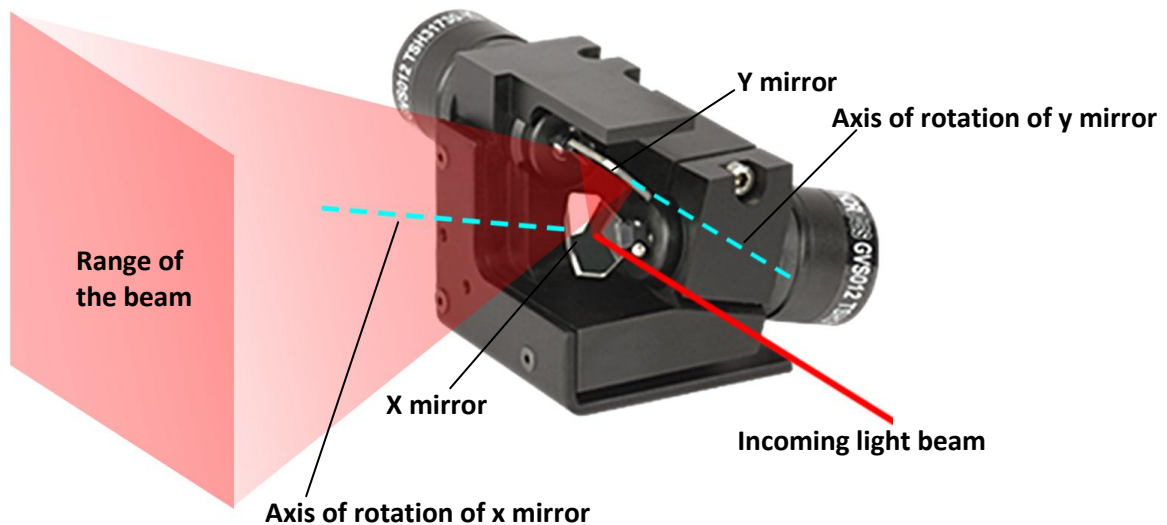


Figure 3.2. The dual-galvanometer, which uses two mirrors to deflect a light beam both horizontally and vertically (adapted from[6])

The galvanometers are connected to two separate driver boards, one for each mirror, which are connected to the DAQ-card of a computer. The DAQ-card provides a signal between +10 V and -10 V to control the position of the mirrors (Figure 3.3).

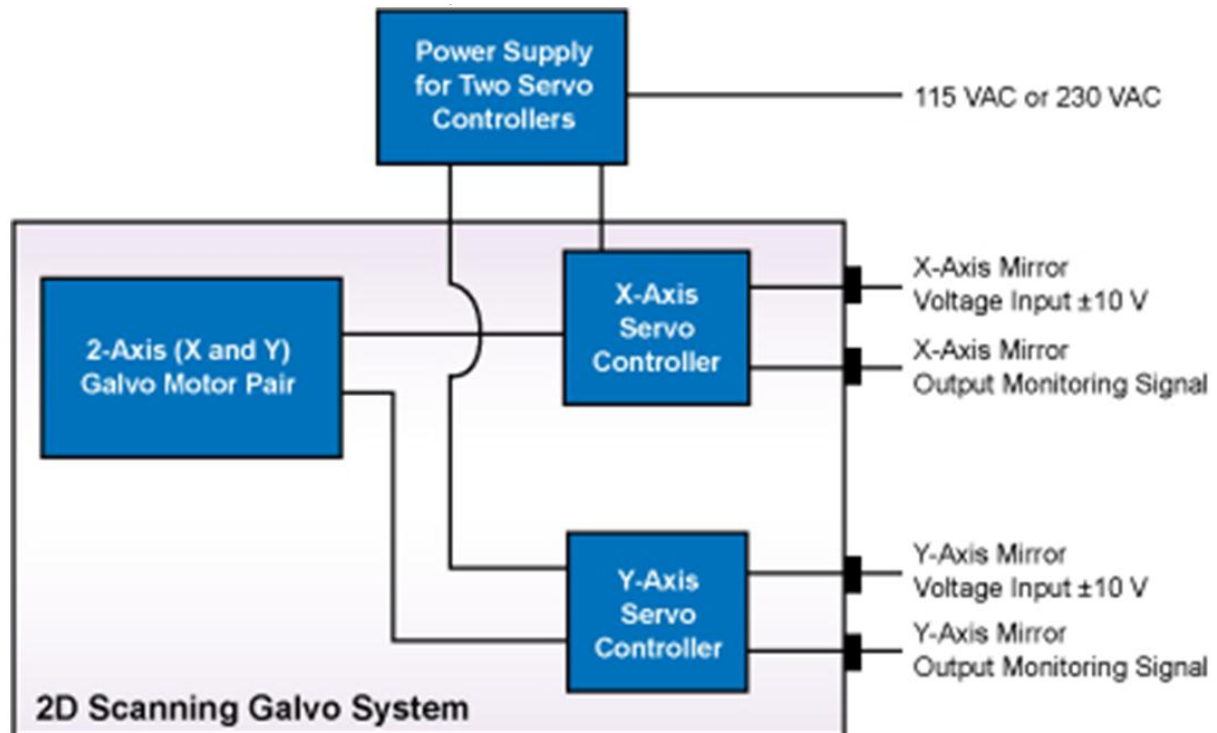


Figure 3.3. A schematic representation of the galvanosystem

4. Methods

In order to perform a volumetric scan with the OCT setup the light beam must be scanned over the surface of the sample. The scanning is done by two galvanometers, which use movable mirrors to reflect the light beam into the desired direction.

A Labview program, describing a model, has been written to control the galvanometers.

To make a volumetric scan, the light beam is scanned in two directions. For example, in the horizontal direction, the beam is scanned back and forth, while in the vertical direction, step by step, it is moved downwards (figure 4.1).

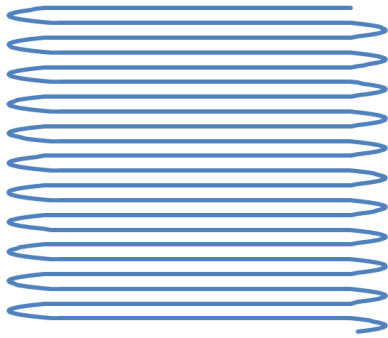


Figure 4.1. An example of a path that the beam can make through the area of interest.

4.1 The model

The fastest scanning movement happens in the horizontal direction. When choosing the motion of the mirrors it must be kept in mind that mechanical stress as a result of large acceleration can damage the mirrors. Therefore, triangular path wouldn't be optimal. The change in speed needs to be gradual, keeping the acceleration small. Besides that, it is desired that when the light beam is moving over a region of interest, the beam has a constant scanning speed. When those two requirements are taken into account a path can be constructed, comparable to the example path in figure 4.2.

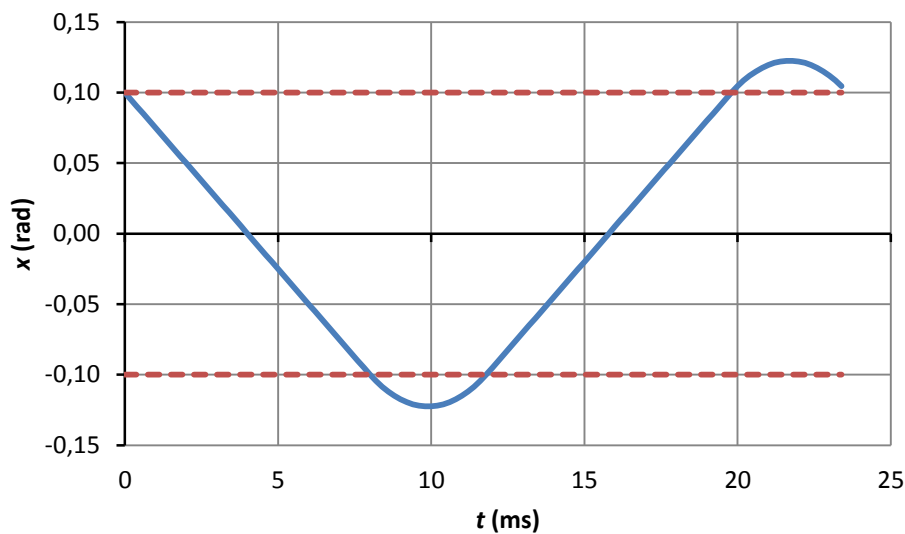


Figure 4.2. An example of a path that the position x can walk through in time t , with a constant speed between the red borders, but “soft” bends to reduce the chance of damage

The steepest slopes are at the linear parts, this maximum slope depends on the speed with which is measured, and the lateral resolution of the setup. The round parts of the path, where the velocity is converted into the opposite direction, may have different shapes. Looking at a harmonic oscillator, part of a sine wave is proposed. Also parabola's are proposed, because those have the property that the speed changes linearly with time. The two shapes are investigated.

In order to characterise the shapes the acceleration will be determined as a function of time and position. This will be done with a continuous wave, without the linear parts, and the general model will be constructed, with linear parts.

Sine function

De waves will be described with the period, and the slope of the linear part. A sine wave without the linear parts as a function of time, period and the maximum slope is given by formula 4.1.

$$x = v_{lin} \cdot \frac{T}{2\pi} \cdot \sin\left(\frac{2\pi \cdot t}{T}\right) \quad (4.1)$$

with:

x :	The position	[rad]
v_{lin} :	The maximum slope	[rad/s]
T :	The period	[s]
t :	Time	[s]

By determining the first and second derivative of the function, the velocity and the acceleration of the mirror are given by formula 4.2 and 4.3.

$$v = v_{lin} \cdot \cos\left(\frac{2\pi \cdot t}{T}\right) \quad (4.2)$$

$$a = -v_{lin} \cdot \frac{2\pi}{T} \cdot \sin\left(\frac{2\pi \cdot t}{T}\right) \quad (4.3)$$

with:

v :	The angular velocity of the mirror	[rad/s]
a :	The angular acceleration of the mirror	[rad/s ²]

The relationship between the acceleration and the position is given by

$$a = -x \cdot \left(\frac{2\pi}{T}\right)^2 \quad (4.4)$$

The acceleration is proportional to the position with a coefficient of $-\left(\frac{2\pi}{T}\right)^2$. The ratio between the acceleration and the position only depends on the period of the path, and not the maximum slope. The relationships given by formulas 4.1 to 4.4 can be seen in figure 4.3. The left column gives the position, velocity and acceleration as a function of time, and the acceleration as a function of position of the sine wave with period T and maximum slope V .

If now the linear part is inserted into the sine wave, the desired path appears. This is done by separating the first and second half of the period, and using those parts to invert the velocity by placing them on top of a linear part. The linear part is placed between two borders, which are chosen by the user. As a result of the extra linear part, the velocity and acceleration change as illustrated in figure 4.3.

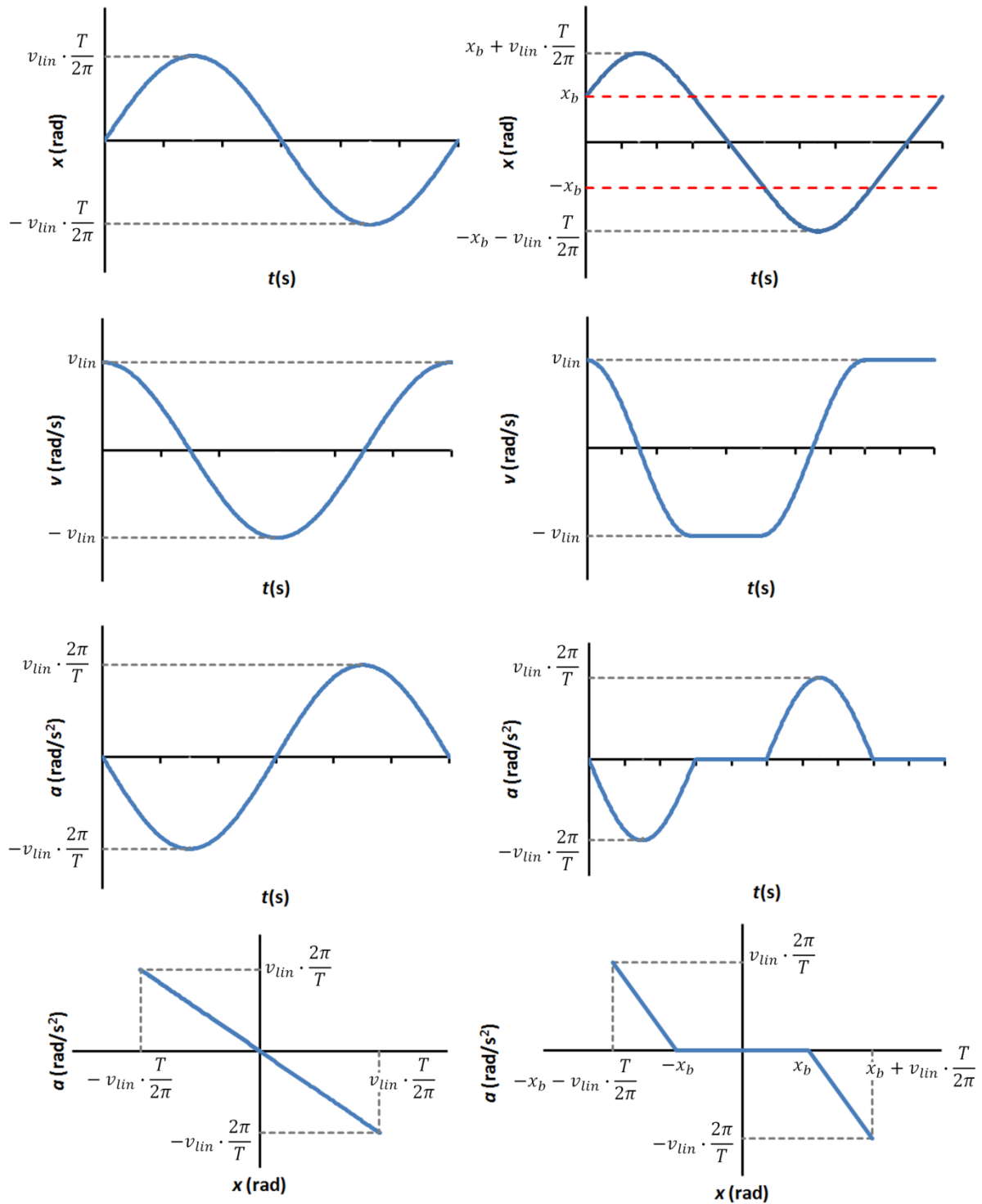


Figure 4.3. At the left the path in the shape of a sine function, with the position, velocity and acceleration as a function of time, and the acceleration as a function of position. On the right a linear part is inserted between borders $+x_g$ and $-x_g$, and the same relationships are given. The borders are chosen by the user.

Parabola

A parabola based waveform will be constructed and to compare to the sine based waveform.

A parabola is constructed which describes half a wave with a maximum one quarter of a period to the right of the vertical axis and a maximum slope, at $t = 0$, of R .

$$x = -v_{lin} \cdot \frac{((t-1/4T)^2 - (1/4T)^2)}{2 \cdot 1/4T} \quad (4.5)$$

This is the first half of the wave, in the shape of the parabola. The second half of the wave can be constructed by multiplying the first half with minus one, and shift it to the right by half a period. This also works for the velocity and acceleration as a function of time.

From formula 4.5, the velocity and acceleration functions can be constructed.

$$v = v_{lin} \cdot \frac{-t}{1/4T} + v_{lin} \quad (4.6)$$

$$a = -\frac{4v_{lin}}{T} \quad (4.7)$$

The absolute value of the acceleration only depends on constants, and is independent of time, within half a wave. In the second half of the wave the acceleration is of the same size, but multiplied by minus one.

The relationships given by formulas 4.5 to 4.7 can be seen in figure 4.4. The left column gives the position, velocity and acceleration as a function of time, and the acceleration as a function of position of the parabola based wave with period T and maximum slope V .

If now the linear part is inserted into the sine wave, the desired path is constructed. As a result of the extra linear part, the velocity and acceleration change as illustrated in figure 4.4. In the right column, the waveform can be seen in which a linear part is inserted between borders $+x_b$ and $-x_b$.

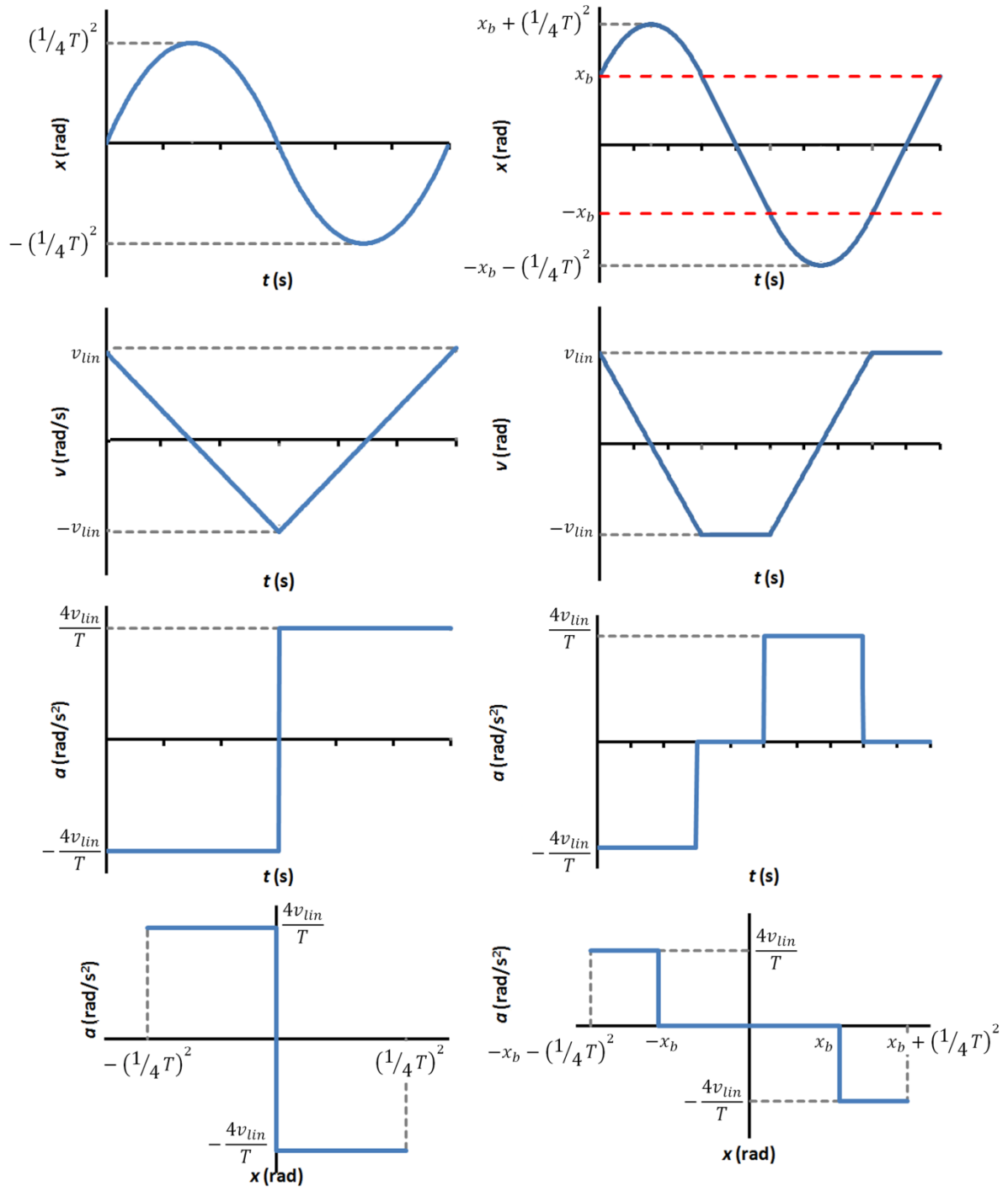


Figure 4.4. At the left column the path constructed with two parabola's, with the position, velocity and acceleration as a function of time, and the acceleration as a function of position . At the right column a linear part is inserted between borders $+x_g$ and $-x_g$, and the same relationships are given.

Comparison

The main difference between the sine based wave and the parabola based wave is the acceleration necessary to make the curve changes over time for the sine, and is constant within one bend for the parabola. Therefore, for the same maximum slope and period the sine based wave gives a higher maximum acceleration than the parabola based wave. The maximum acceleration of the sine based wave equals $v_{lin} \cdot \frac{2\pi}{T}$ and for the parabola based waveform it equals $v_{lin} \cdot \frac{4}{T}$. As a result, this gives a smaller maximum amplitude for the parabola based wave.

In order to prevent damages, the parabola based wave is chosen, because the forces as a result of the acceleration are kept to a minimum.

Besides the horizontal movement of the beam, it also needs to be moved vertically. This will be discussed later on.

4.2 Labview program

To generate the signal that will control the galvo system, National Instruments Labview Software is used. A program is written that calculates all the positions that form the path. The positions are collected in a array that is sent to the galvo system.

The arrays are constructed by starting with an initial position and calculate the next position from that by adding the change in position at that moment. With the new position the next position can be calculated, and so on (figure 4.5 a). In the same way the velocity can be calculated with a given acceleration (figure 4.5 b).

This is done with a feedback node, which, when placed in a loop, will delay a value with one iteration, giving the previous value [7].

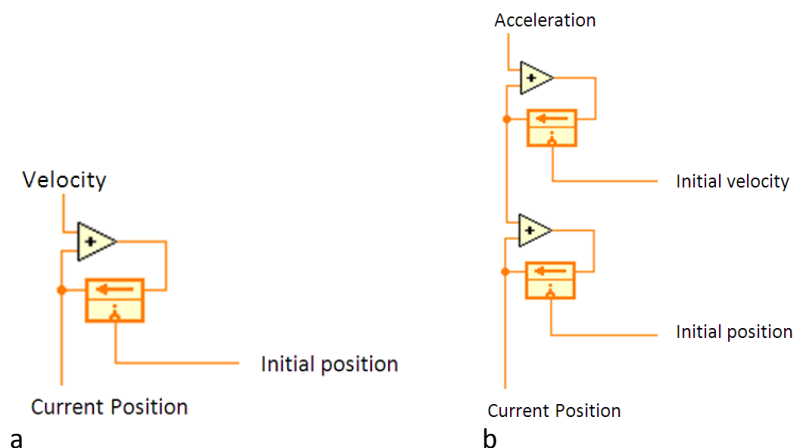


Figure 4.5. a) the current position is calculated by adding the velocity to the previous position. b) The new position can be calculated using the velocity, which can be calculated with the acceleration.

In this way, the path of the galvanometers is not continuous, but it is calculated with fixed steps. The velocity is the change in position for the time between two iterations, and the acceleration is the change in velocity for the time between two iterations.

The program consists of several parts, which are run sequentially:

1. First the desired settings are chosen. These settings will be checked by the program by calculating that running with the chosen settings will not exceed any of the galvo systems limits.
2. Before the scanning can be started, the galvo mirrors need to be brought to the right starting position and velocity. In the second part of the program, this is done.
3. Immediately after this, the scanning begins. The complete area that is selected is measured.
4. After the measuring, the galvo mirrors are brought to a controlled stop.

1. Choosing and checking the variables

A user can enter the lateral resolution of the setup, the maximum acceleration of the galvanometers and the borders between which will be measured, to describe the desired path. Here the resolution is the distance between two measurements, which take place in the linear part between the borders. Not all combinations of settings are possible, there are a few conditions. The resolution is always a multiple of the maximum acceleration, and the borders are always a multiple of the resolution. In this way there are always a whole number of measurements between two borders, and it always takes a whole number of steps to accelerate from standstill to a velocity of one resolution per iteration.

Every value can be entered, but will be rounded in a way to meets the conditions.

These conditions are chosen, because the path is not continuous. It is calculated in steps.

When the settings are determined, the program computes the maximum amplitude of the path. Because the path is constructed by calculating a number of separate steps, with a fixed time in between the steps, this is not exactly the same as for a regular parabola.

If the position of the maximum exceeds the capacity of the galvanometers, the program will not continue and show a warning.

The difference between two following positions can be seen as a measure for velocity, although this is an angle. In the linear part, this difference between sequential positions is constant. At the parabola's it changes gradually, which can be shown as a measure for acceleration, although this difference between tow sequential position differences is still an angle. In formula form

$$\Delta x = V \quad (4.8)$$

$$\Delta V = A \quad (4.9)$$

with:

x :	The position	[rad]
V :	The difference between two sequential positions	[rad]
A :	The difference between two sequential position differences	[rad]

The position of the maximum consists of the height of the border x_b , plus the height of the bend on top of it.

The number of steps it takes to decelerate from the velocity at the linear part V_{lin} to zero, equals $\frac{V_{lin}}{A_{max}}$. In order to decelerate the velocity decreases with a every step.

Therefore the position of the maximum can be expressed with the following formula.

$$x_{max} = x_b + V_{lin} \cdot \frac{V_{lin}}{A_{max}} - A_{max} \cdot \sum_{i=0}^{\frac{V_{lin}}{A_{max}}} i \quad (4.10)$$

with:

x_{max} :	The position of the maximum	[rad]
V_{lin} :	The difference between two sequential position in the linear part	[rad]
A_{max} :	The difference between two sequential position differences	[rad]

The summation can be rewritten as a parabolic function.

$$x_{max} = x_b + \frac{1}{2} \left(\frac{V_{lin}^2}{A_{max}} - V_{lin} \right) \quad (4.11)$$

The transformation from the summation to the parabolic function can be found in Appendix 2. The maximum position is compared with the capabilities of the galvanometers. If it exceeds the capabilities, the scanning will not be started, and a warning message is shown.

2. Bringing the galvanometers to the initial position and velocity

In the second part of the program, the current positions of the galvo mirrors are measured. A path is calculated from that position to the starting position. This is done by calculating the difference between the current position and the position where the beam starts the scanning. The number of steps it takes to cover this distance when the velocity equals the chosen number for a is calculated. This means that starting and ending this movement requires an acceleration of a , which equals the maximum acceleration of the galvanometers. In this way an array of positions is constructed, which is sent to the DAQ-cart.

3. Scanning

The waveform of the horizontal movement can be divided into four sections (figure 4.6).

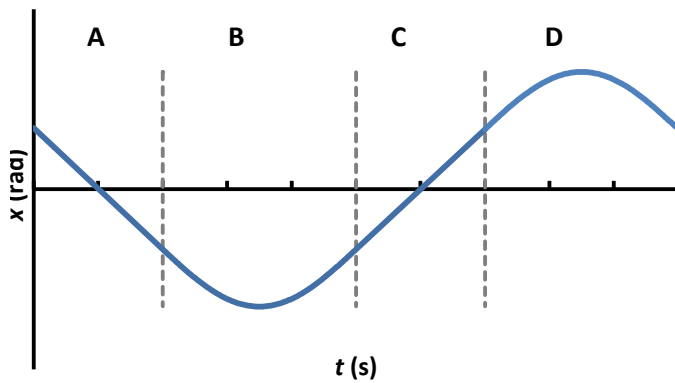


Figure 4.6. The four sections of the wave

In sections A and C, the galvo mirror moves with constant velocity and the measurements are performed. During sections B and D the velocity of the mirror is inverted.

The length of the sections, in iterations, depends on the chosen settings. These lengths can be found in table 4.1.

Table 4.1. The lengths of the different sections of the waveform

Section	Length
A	$2 \cdot \frac{x_b}{V_{lin}}$
B	$2 \cdot \frac{V_{lin}}{A_{max}}$
C	$2 \cdot \frac{x_b}{V_{lin}}$
D	$2 \cdot \frac{V_{lin}}{A_{max}}$

The quantities in table 4.1 already meet the conditions that are set in the first part of the program. In order to make a volumetric scan, the beam must be moved in the y-direction as well. This is done in sections B and C. The change in position between two B-scans equals V_{lin} . Because the length of sections B and D in iterations is $2 \cdot \frac{V_{lin}}{A_{max}}$, the y-position can be changed with a constant velocity of $\frac{a}{2}$. The maximum acceleration is $\frac{A_{max}}{2}$. This results in a path as shown in figure 4.7.

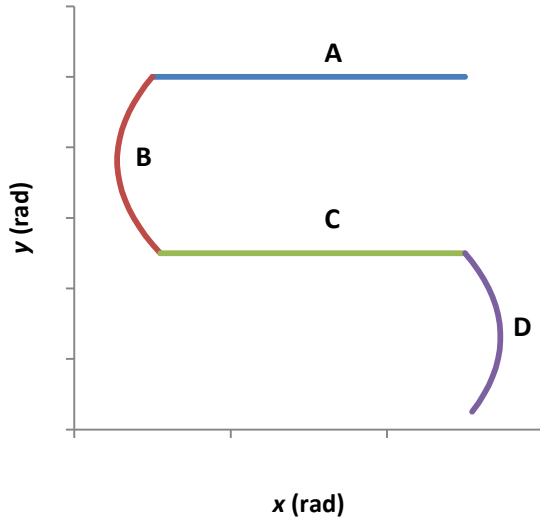


Figure 4.7. An example of the path as the result of one single wave, divided in sections

In the program the length of the sections is calculated, and for each section the required initial velocity and acceleration is taken from the settings to calculate the path of that section, with the method from the beginning of paragraph 4.2. All of this together forms one array which can be send to the DAQ-card.

Before the scanning begins the mirrors are first accelerated in to the right direction by adding half a parabola in front of the path of the figure 4.6.

Besides controlling the galvanometers, a signal is also sent to the spectrometer to time the measurements. A Boolean array is constructed which gives a high signal to at sections A and C to indicate that at that time the measurements need to be performed.

4. Bringing the galvanometers to a controlled stop

The galvanometer for the horizontal movement is stopped by creating an array which describes a path which consists of half a parabola to bring the mirror to a controlled stop. The velocity of the galvanometer for the vertical movement is always low enough to safely stop the mirror at once.

5. Results

The Labview program is written, resulting in a flexible way to control galvanometers.

A user can insert the lateral resolution of the setup, the maximum allowed acceleration of the galvanometers, the borders between which the measurements need to take place and the time between two sequential points of the path. The program protects the galvanometers against running with settings that might damage the mirrors.

Before the scanning starts the position of the galvanometers is brought to the initial position for the scanning. Then, the program computes a path, using parabola's to invert the velocity, but with linear parts in the region of interest for the measurements. Afterwards it is brought back to the default position.

Figure 5.1 shows an example of the motion in the x and y direction. The horizontal axis shows the "iterations". This is a measure of time. In this case, with a camera line-rate of 50 kHz, the duration of one iteration equals $2.0 \cdot 10^{-5}$ s.

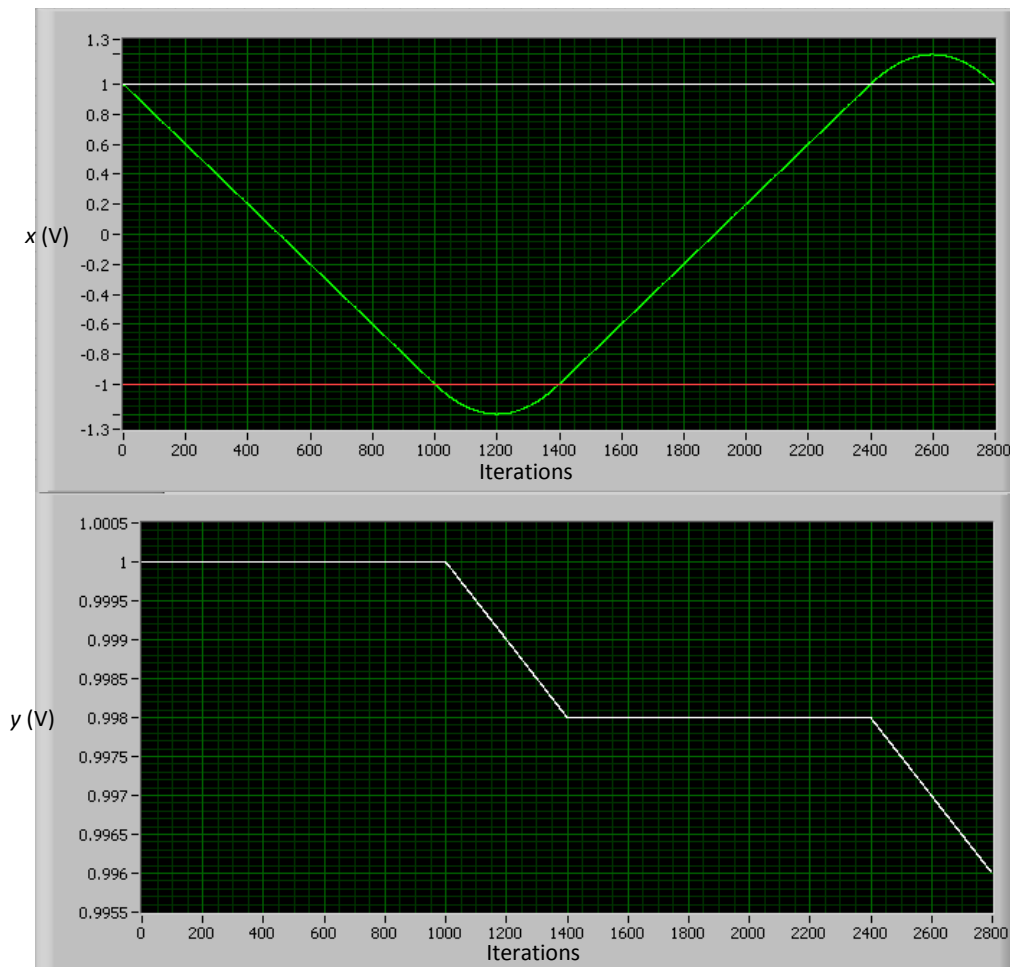


Figure 5.1. An example of one period of the waves that control the x and y movement of the galvanometers. The used settings are as following: a lateral resolution (V_{lin}) of 0.002 rad, the borders between which is measured are both 1.0 rad, and a maximum acceleration of 0.5 rad/s^2

6. Discussion

The program that is written can be a flexible way to control galvanometers. It can be easily adjusted to the user's desires. The light beam is scanned with a constant velocity over the region of interest, and the measurements are triggered by a Boolean signal. This gives the possibility to calculate the position of every measurement, and construct a three-dimensional image. Also, the program protects the galvanometers against running with settings that might damage the mirrors.

Although the signals that are generated by the program are as desired, the code to send the signal to the DAQ-card, to send it to the galvo system, caused challenges in the development. Because the output signal of the computer was not reliable, it was never used to control the galvanometers. Further steps can be taken to perfect the communication between soft- and hardware, to allow the usage of the galvanometers without the risk of damaging them.

The written program does not use the possibility of the galvanometers to measure the current position. This can give information about the delay between the signal that is used to control the galvanometer and the actual motion of the mirrors.

Furthermore, according to the user manual, the used galvanometer is able to perform waveforms with a frequency of 65 Hz, and a sine wave with a frequency up to 135 Hz [6]. Because the galvanometers will typically move with a frequency around 25 Hz, this shouldn't cause any problems, although a certain delay is expected. Factory specifications do not provide a maximum allowed acceleration. Future research could be done to investigate the capabilities of the galvanometers, to allow users to use it with optimal settings.

7. Conclusion

In order to control a duo-galvanometer system a National Instruments Labview computer program is written to perform FD-OCT measurements. The program creates a path for both the x and y mirror to follow by calculating every positions out of the previous position using feedback nodes.

The path for the x mirror consists of linear parts for the scanning, and parabolas to invert the velocity. Because the velocity of the y mirror stays relatively low, the velocity does not need to change gradually. Before the scanning starts, the amplitude of the signal is calculated for the current settings, only when those do not exceed the capabilities of the galvanometers, the scanning can start. Also the mirrors are brought from the default position, to the starting position and after the scanning, the they are brought back to the default position.

8. Sources

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Appendix 1. Original assignment

The original assignment for the bachelor internship is not the assignment that eventually is completed. Originally a MEMS OCT probe would be investigated and characterized. Because the probe disintegrated at the first time it was connected with its laser sources, this assignment could not be completed. The assignment description is given in Dutch:

Titel: MEMS endoscope voor OCT applicaties

Achtergrond

OCT

Optische coherentietomografie (OCT) is een onderzoekmethode voor deels reflecterende (opake) materialen, waarbij beelden (dwarsdoorsneden) worden gevormd met behulp van een interferometer voor licht met een geringe coherentielengte. Vergeleken met concurrerende methoden is de indringdiepte (1-3 mm) in verstrooiend weefsel klein maar de diepteresolutie (0,5-15 μm) groot, bij een hoge meetsnelheid (20-300 kvoxel/s). De methode is te vergelijken met echografie, waarbij geluid wordt gebruikt in plaats van licht.

OCT wordt onder meer in de oogheelkunde gebruikt om het netvlies te onderzoeken. Resoluties van 10 μm zijn haalbaar, waarmee deze techniek kleinere details zichtbaar maakt dan echografie of MRI. De resolutie is vergelijkbaar met die van een zwakke microscoop. De methode kan beschouwd worden als een optisch equivalent van de echografie. De weerkaatste lichtgolven worden gebruikt om een dwarsdoorsnede van het weefsel te reconstrueren. De methode is non-invasief, dat wil zeggen dat er geen enkel materiaal of gereedschap in het lichaam wordt gebracht; er wordt dan ook geen incisie gemaakt. De enige voorbereiding bestaat uit het toedienen van pupilverwijdende druppels.

De belangrijkste voordelen van OCT zijn:

- rechtstreekse beelden van het inwendige van het weefsel, met bijna-microscopische resolutie
- geen voorbereiding van preparaten of van de patiënt nodig
- geen ioniserende straling.

MEMS

AMC en Innoluce ontwikkelt en verkoopt een optische component die zelfs in een zeer kleine omgeving laserlicht snel weet af te buigen. Deze component noemen we laserscannermodule (LSM), waarvan het hart gevormd wordt door een resonante Micro Electro Mechanical System (MEMS) spiegel vervaardigd uit silicium.

De student zal zich tijdens de stage periode bezighouden met twee specifieke taken

- a) Het implementeren van een MEMS endoscope in een bestaand OCT systeem
- b) Het testen van de optische eigenschappen van de MEMS endoscope

Because the original assignment could not be completed, a comparable assignment was appointed to the student. The student would be involved in the PhD research to help build a OCT setup, and write the National Instruments Labview program to control the setups galvanometer system.

Appendix 2. The transformation from summation to quadratic equation

Given is the following summation.

$$T(n) = \sum_{i=1}^n i \quad (1)$$

In order to rewrite this summation as a function, it is written as following.

$$T(n) = 1 + 2 + 3 + \dots + (n - 2) + (n - 1) + n \quad (2)$$

By multiplying by two, the following is accomplished.

$$\begin{aligned} 2T(n) &= 1 + 2 + 3 + \dots + (n - 2) + (n - 1) + n \\ &\quad + n + (n - 1) + (n - 2) + \dots + 3 + 2 + 1 \end{aligned} \quad (3)$$

This can be rewritten to a plurality of the same term.

$$\begin{aligned} 2T(n) &= (1 + n) + (2 + (n - 1)) + (3 + (n - 2)) + \dots \\ &\quad + ((n - 2) + 3) + ((n - 1) + 2) + (n + 1) \\ 2T(n) &= (n + 1) + (n + 1) + (n + 1) + \dots \\ &\quad + (n + 1) + (n + 1) + (n + 1) \end{aligned} \quad (4)$$

The amount of $(n + 1)$ terms equals n , which means that this can be rewritten as a multiplication.

$$2T(n) = n \cdot (n + 1) \quad (5)$$

By dividing by two, a function is found for $T(n)$.

$$T(n) = \frac{n \cdot (n + 1)}{2} = \frac{1}{2} \cdot n \cdot (n + 1) \quad (6)$$