CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING INFORMATION AND AUTOMATION TECHNOLOGY

Methods of Precise Remote Distance Measurement

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1) Review of instruments for precise remote distance measurement, summarize different techniques, it's needs for technical realization, range, and resolution of measurement.
2) Propose remote distance measurement task realized with optical sensors available in our department.
3) Perform distance and glass thickness measurement with triangulation and confocal sensor.

Bibliography / sources:

[1] Max Born and Emil Wolf, Principles of optics : electromagnetic theory of propagation, interference and diffraction of light, 1999
[2] Wiliams D. C.: Optical Methods in Engineering Metrology, Chapman&Hall, 1993
[3] A. Ahmad and V.Genberg, Optomechanical Engineering Handbook, 1st ed. Boca Raton, Florida, USA: CRC Press LLC, 1999

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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Statement

I hereby declare that I have prepared this bachelor thesis independently, under the guidance of my supervisor Doc Ing. Jan Hošek, Ph.D, using the literature and material listed at the end, in the references.

Prague 2023

…………………………………….

Signature

Acknowledgements

I would like to express my sincere gratitude to my supervisor Doc Ing. Jan Hošek, Ph.D who advised and piqued my interest into the subject with his enthusiasm. Most importantly, I thank him for is invaluable time he made available to me.

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Abstract

This thesis was conducted at and assigned by Czech Technical University in Prague, further CTU, and used CTU's resources available to me as a student.

This thesis examines three prominent techniques for precise remote distance measurement: confocal chromatic, laser interferometer, and laser triangulation. Each method is analyzed in terms of its principles, instrumentation, limitations, and practical considerations.

The confocal chromatic method utilizes chromatic aberration principles to achieve highly accurate distance measurements. By employing a spectrally dispersed light source and a confocal sensor, it offers excellent axial resolution and immunity to surface variations. This thesis explores the underlying principles, instrumentation, and implementation considerations of confocal chromatic measurement.

Laser interferometry is a widely used technique that exploits laser beam interference for precise distance measurement. I will investigate the theory, principles, technical requirements, and various configurations of laser interferometers, along with challenges related to environmental disturbances and fringe analysis techniques.

Laser triangulation, another non-contact method, relies on the triangulation principle to remotely measure distances. It projects a laser beam onto a target and captures the reflected light on a position-sensitive detector. The following will cover the theoretical foundations, instrumentation, and factors affecting accuracy in laser triangulation, as well as addressing a few challenges such as surface reflectivity and target orientation.

Throughout the thesis, a comparative analysis of these three methods is presented, highlighting their respective strengths, limitations, and applicability in different scenarios. Parameters such as measurement range, resolution, speed, environmental robustness, and cost are considered to facilitate informed decision-making in selecting the most suitable technique.

The insights and findings presented in this thesis contribute to a better understanding of confocal chromatic, laser interferometry, and laser triangulation as methods for precise remote distance measurement. This knowledge can aid researchers, engineers, and practitioners in choosing and optimizing the most appropriate method for their specific measurement requirements, which in turn prepares those such as myself for experiments with these instruments.

Keywords

confocal chromatic measurement, laser triangulation, stick-slip piezo motor

Annotation List

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Abbreviations

CCD	Charge-Coupled Device

Units

nm	nanometer
μm	micrometer
mm	millimeter
kHz	kilohertz

1. Introduction

Non-contact measurements are typically conducted by some form of optical method. These optical methods can range from laser interferometry, optical profiling, confocal and laser triangulation and more. In the following chapters I will present a few of these optical methods and their measurement principles.

With the rise of high precision machining, additive manufacturing and automated assembly there is an ever-increasing need for precise displacement measurements. In my own experience as a mechanical design intern, there was excessive amounts of time spent on validation of parts which would then stall assembly. For many external measurements, a mounted displacement sensor would enable swift tolerance checks akin checkout at a grocery store.

The goal of this thesis is to shed light on the precision of the non-contact sensors as a viable replacement for contact measurement instruments in specific environments as well as to highlight the importance of selection of sensors based on individual requirement.

This thesis is divided into 9 chapters, where chapters 2 to 4 will discuss different sensors and their capabilities. The following chapters 5-8 presents an experimental analysis of two of the previously discussed sensors.

2. Confocal Chromatic Measurement Principle

2.1 Introduction

Confocal chromatic measurement is a technique used in metrology for the precise measurement of surfaces. The principle is based on confocal microscopy, which uses a pinhole to eliminate out-of-focus light, and chromatic aberration, which allows for the determination of the distance between the pinhole and the surface being measured.

2.2 Principle

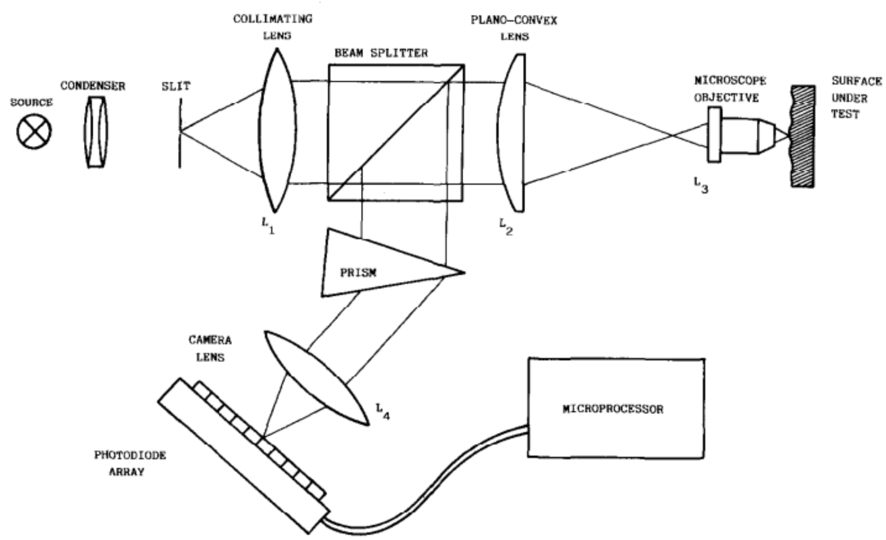


Figure 1 Schematic diagram of an original optical profilometer (G. Molesini)

The figure 1 above is one if the first method of optical profilometry, by G. Molesini in 1984, and the depth of surface is measured by the position on a photodiode array. The planoconvex lens can be denoted as a longitudinal dispersion lens and the prism would a be a lateral dispersion lens. Calibration for legible results was done by a mirror in the place of the sample, which was part of a Michelson interferometer, afterwhich the depth was controlled by a fringe counter.

One fringe would correspond to a mirror displacement of one-hald wavelength, the max intensity diode is then mapped to said frequency which produced the following graph, figure 2. [1]

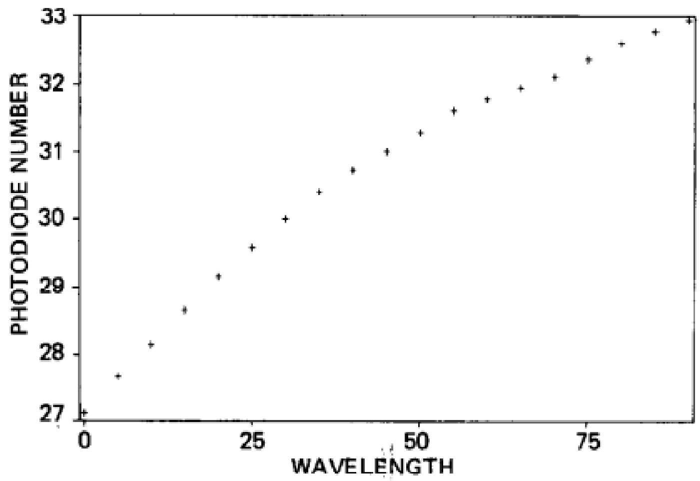


Figure 2 Calibration curve of the of the peak position on the linear photodiode array as a function of the sample displacement (G. Molesini)

Confocal microscopy is a technique that uses a pinhole to eliminate out-of-focus light. The pinhole is placed at the focal point of the microscope objective, and light from the specimen is focused through the pinhole onto a detector. In confocal microscopy, the pinhole acts as a spatial filter, allowing only light from a specific plane to pass through. This eliminates the problem of out-of-focus light, which can reduce image contrast and resolution. [2]

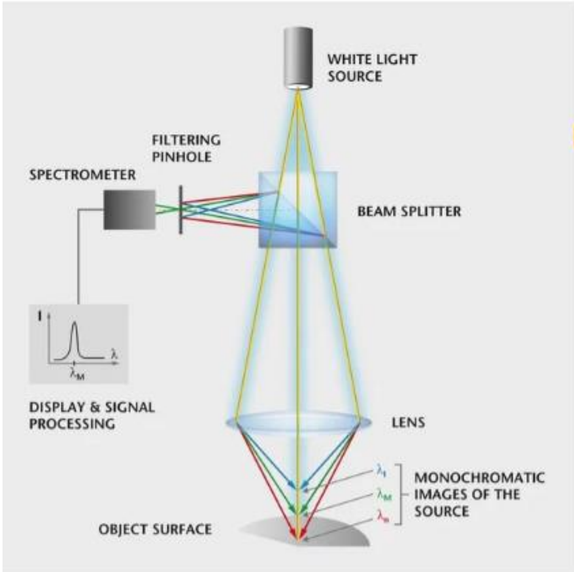


Figure 3 Simplified example of confocal chromatic measurement apparatus (Polytec)

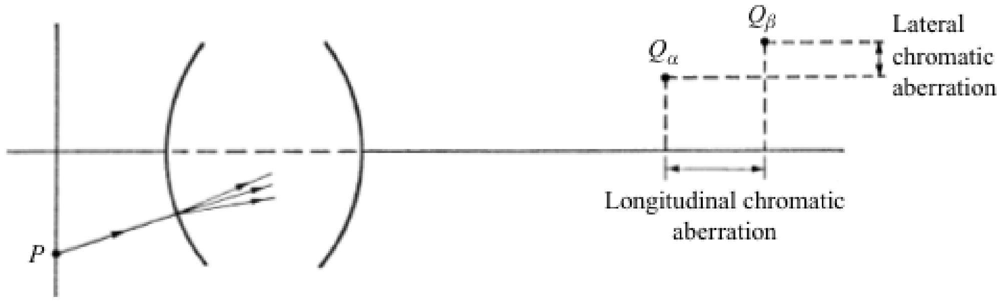


Figure 4 Chromatic Aberrations (Max Born)

Chromatic aberration is the phenomenon where polychromatic light which contains multiple wavelengths of light also have a their own respective refractive indices through a lens or optical system and are refracted differently by a lens, resulting in different focal lengths for different colors of light focusing along the same center axis in confocal spectrometry. Confocal chromatic measurement makes use of chromatic aberration of light to determine the distance between the pinhole and the surface being measured. [3]

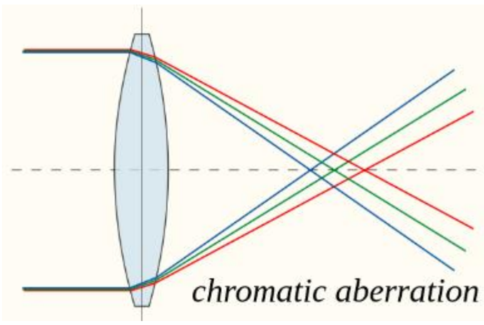


Figure 5 Useful Chromatic Aberration in Measurements (Theta360)

In confocal chromatic measurement, a broadband light source(wide range of wavelengths) is used to illuminate the surface being measured. The light is then focused through a lens onto a pinhole, which acts as a spatial filter cleaning up the ouput and aberrations in the beam. The pinhole is then imaged onto a spectrometer, which measures the wavelength of the light passing through the pinhole, this wavelength is dependent on the distance between the pinhole and the surface being measured, due to chromatic aberration. [4]

2.3 Operational Requirements

1. Light source; A broadband light source is required, it should have a broad spectrum to ensure that all wavelengths of light are present. Stable intensity for consistent measurements.

2. Optics; Higher quality optics are essential, the lens used to focus the light onto the pinhole should have a high numerical aperture which ensures a good resolution. The pinhole need be refined and precise for the best results. [5]

3. Spectrometer; Required to analyze the spectrum of the light passing through the pinhole it needs a high resolution and sensitivity to ensure accurate measurements.

4. Detector; A detector is required to capture the signal from the spectrometer it needs a high sensitivity and low noise to ensure accurate measurements. [6]

5. Calibration; The confocal system needs to be calibrated when necessary to a standardized part of know dimensions, which helps keep accuracy in measurements.

6. Environmental conditions; The measurement system is sensitive to environmental conditions such as temperature and humidity. The system should be operated in a stable environment with a controlled temperature and humidity to ensure consistent measurements per task. [7]

7. Sample preparation; The surface being measured should be clean and free from any debris, this prevents any unexpected and incorrect results.

8. Operator expertise; Confocal chromatic measurement requires a higher level of expertise for the understanding of working principles and troubleshooting.

2.4 Range and Resolution

The range and resolution of the confocal chromatic measurement principle depend on a couple of factors such as the numerical aperture of the lens, the pinhole diamter, and the spectral range of the light source. From the user point of view you can not change much after buying a sensor for its specific purpose and a differently setup sensor for another measurement. The range of confocal chromatic measurement is typically in the micrometer to millimeter range. The measurement range is determined by the depth of field of the optical system, usually around a few micrometers. By using different lenses with varying depths of field, the measurement range can be extended, however this comes at the expense of resolution.

For example, a confocal chromatic displacement sensor produced by Keyence Corporation CL-3000 series has a measurement range of 10 mm and a resolution of 1 nm. The sensor uses a broadband light source with a wavelength range of 400 to 1100 nm. [8] Whereas, another example is the MicroProf® 200 from FRT, which is a confocal chromatic profilometer used for surface topography measurements. The system uses a white light LED as the light source with a wavelength range of 400 to 1000. The system can achieve a measurement range of up to 600 μm with a vertical resolution of 6 nm. [9]

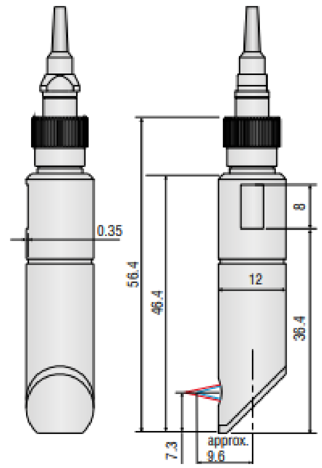


Figure 6 ConfocalDT IFS2404/90-2 sensor (Micro-Epsilon)

Or another example, the sensor used in the following experiments, Micro-Epsilon confocalDT IFS240, figure 6. This precise sensor has a measuring range of 2mm with the start of measuring range at 9.6mm, and a resolution of 40nm.

In summary, the range and resolution of these confocal sensors require specific configurations for to have either preferred variable as well as the 90 degree sensor above which makes it ideal for various tight configurations.

2.5 Advantages

- High precision, this technique can achieve sub-micron precision, making it useful for measuring surfaces with high precision requirements.
- Non-contact nature, does not require physical contact with the surface being measured, which can be useful for measuring delicate or fragile surfaces.
- Insensitivity to surface reflectivity, you can measure the thickness of glass using the distinctive peaks. [10]

2.6 Limitations

- There is a limited measurement range which can be too small for use of one sensor in varied applications, the sample needs to fit the measuring range especially in thickness measurements oriented towards placing the specimen in the middle of the range. [11]
- Sensitivity to the refractive index is set assuming the uniformity of the material, such as glass set to Bk7 is expected that all the layers are of the said refractive index.
- Althought almost anyone with any amount of technical know how could setup the measurement task it still needs to be treated carefully as the stage separation and the sensor start of measurement range can be mistaken often. On the other hand you may view graphically displayed data but the programs still tend to output raw data which can take some expertise to manipulate appropriately.

2.7 Applications of Confocal Chromatic Measurement

Confocal chromatic measurement has a wide range of applications in various industries. One application is in the semiconductor industry, where it is used for the measurement of the thickness of thin films and its uniformity. [12]

The technique is also used in the automotive industry for the measurement of the surface roughness of engine components, non contact nature enables there to be no wear on either the measurement tool or sample.

Confocal chromatic measurement is also used in the medical industry for the measurement of the surface roughness of dental implants, the high precision being the sought after property here.

Surface profilometry, the surface profile of various materials such as semiconductor wafers, optical components (lens curvature), and biomedical implants. The technique provides sub-micrometer resolution and can measure surface features such as roughness, step heights, and surface defects. [13]

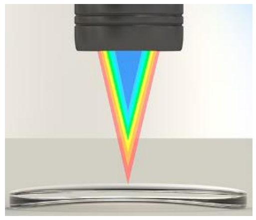


Figure 7 Surface Profilometry (Micro-Epsilon)

3. Laser Interferometer

3.1 Introduction

Laser interferometers are widely used in science and engineering to measure distances with high accuracy. Working on the principle of interference of light waves and provide measurements that are accurate to a fraction of a wavelength of light.

3.2 Working Principle

Laser interferometers work on the principle of interference of light waves to measure distances with high accuracy, using a laser beam that is split into two or more beams that travel along different paths and are then recombined to produce interference patterns.

The interference patterns produced by the recombined beams can be used to determine the difference in distance traveled by each beam. This difference in distance can be used to calculate the distance to the object being measured. The accuracy of the measurement is determined by the wavelength of the laser beam used. [14]

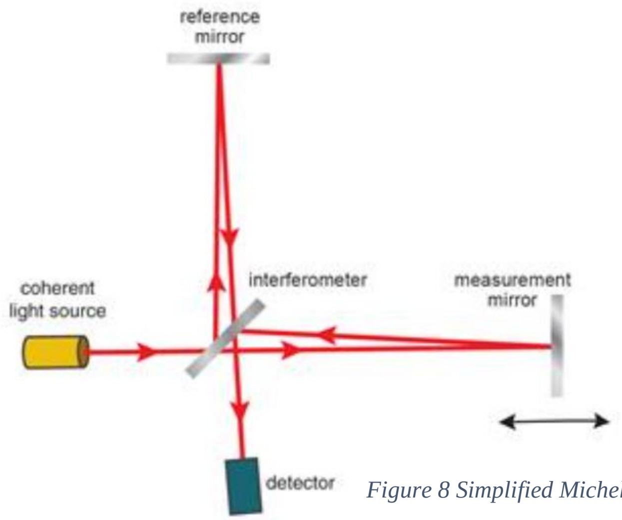


Figure 8 Simplified Michelson Interferometer (Renishaw)

One of the most common types of laser interferometers is the Michelson interferometer. The interferometer consists of a beam splitter that splits the laser beam into two beams that travel along different paths before being recombined by a mirror. The interference pattern produced by the recombined beams is detected then analyzed to determine the difference in distanc e traveled by each beam. The Michelson interferometer is often used in applications that require high precision, such as in the field of optics and semiconductor manufacturing. It is also used in astronomy to measure the distance to stars and galaxies.

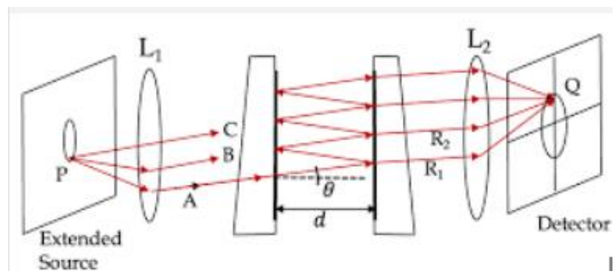


Figure 9 Fabry-Perot Interferometer (Physicsbootcamp)

On the right is another interferometer known as a Fabry-Perot interferometer. It consists of two mirrors, polished to a high degree of flatness [15], that are separated by a distance equivalent to that of an integer multiple of the wavelength of the laser beam. This interferometer consists of a laser beam that is directed onto a partially reflective mirror, which reflects part of the beam while allowing the rest to pass through, the reflected beam is directed onto a second partially reflective mirror, which reflects part of the beam back onto the first mirror. The beam is reflected back and forth between the two mirrors which produces interference patterns that can be detected then analyzed to determine the distance to the object being measured.

A very important Michelson Interferometer worth mentioning is the LIGO, Laser Interferometer Gravitational-Wave Observatory. Invented in the 1880’s, the arms span 4km long, as the longer the interferometer the smaller the measurements it can make. To further increase the sensitivity a fabry-perot cavity is introduced where mirrors are placed on the “Michelson” arms increasing the laser travel distance from 4km to an astonishing1200km.

Other types of laser interferometers include homodyne interferometer that uses a single laser frequency and heterodyne interferometer uses two different but close in value frequencies for its laser. [16]

3.3 Operational Requirements

some of the key requirements:

1. Laser stability; Laser interferometers require a stable laser source with a fixed wavelength and low noise to produce reliable interference patterns, high precision equals distinct fringes. [14]

2. Optics stability; The interferometer optics, such as mirrors and beam splitters, must be stable and well-aligned to prevent any fluctuations or misalignments that could affect the accuracy of the measurements.

3. Environmental control; the interferometers are sensitive to changes in temperature, humidity, and air pressure. Therefore, it is important to maintain a stable and controlled environment during operation.

4. Vibration isolation; External vibrations, such as those caused by machinery or foot traffic, can disrupt the accuracy of the measurements. Laser interferometers require a vibration-isolated platform or enclosure to minimize these effects.

5. Calibration; Laser interferometers must be calibrated periodically to ensure their accuracy. Calibration involves comparing the interferometer readings to a known standard and adjusting the interferometer as needed.

6. Data analysis; Interference patterns produced by laser interferometers require careful analysis to extract accurate measurements. Advanced signal processing and data analysis techniques are used to analyze the interference patterns and calculate distances or other parameters.

3.4 Range and Resolution

The range of a laser interferometer is determined by the distance that the laser beam can travel and still produce a detectable interference pattern, different interferometers can vary widely, from micrometers to kilometers. A Michelson interferometer can typically measure distances up to a few meters, while a Fabry-Perot interferometer can measure distances up to several kilometers.

The resolution of a laser interferometer is based on the smallest change in distance that can be detected by the interferometer. The resolution is defined by the distance between the telescopes, rather in a Michelson interferometer the maximum displacement of the moving mirror [17]. A Michelson interferometer has a resolution of a few nanometres and the Fabry-Perot innterferometer is a few micrometres.

There is a balance between range and resolution, interferometers with a long range typically have lower resolution, while interferometers with high resolution typically have a shorter range. However, there are some interferometers that can achieve a considerable high range and high resolution, such as the heterodyne interferometer can measure distances up to several meters with a resolution of a few nanometers or better.

3.5 Advantages

1. High precision; capable of very high precision measurements, with resolutions in the sub-nanometer range.

2. Non-contact measurement; measuring displacement or distance without making physical contact with the object being measured.

3. High stability; they are highly stable and can provide accurate measurements over long periods of time.

4. Wide range with different setup, different types of laser interferometers have different ranges, from micrometers to several kilometers.

5. Fast measurement; capable of making measurements very quickly, allowing for real-time monitoring and analysis.

6. Detection of gravitaitonal waves by Laser Interferometer Gravitational-Wave Observatory (LIGO).

3.6 Limitations

However, their limitations need to be considered when selecting the right measurement tool,

1. Sensitivity to environmental factors; Laser interferometers require a controlled environment can be affected by changes in temperature, air pressure, and vibrations, which can cause errors in the measurements.

Primary limitation of ground based inteferometry is the turbulent atmosphere. [18]

2. Line-of-sight requirement; Laser interferometers require an unobstructed line of sight between the instrument and the object being measured, which may limit their use in certain applications.

3. Cost; the interferometers can be expensive and need to be viable in from the cost effectiveness in some experiments.

4. Complexity; Laser interferometers are complex instruments that require careful alignment and calibration to ensure accurate measurements this would require a general expertise from the user which can limits its functionality.

5. Limited measurement range; While it’s a positive there is no one size fits all so different applications would require different range interferometers.

3.7 Applications of Laser Interferometer

1. Precision manufacturing, processes such as semiconductor fabrication, where high-precision measurements are required to ensure product quality.

2. Astronomy, to measure the position and motion of stars and galaxies, and to detect gravitational waves.

3. Metrology, to calibrate measurement instruments and to verify the accuracy of standards and reference materials. [19]

4. Biomedical research, to measure the mechanical properties of biological tissues and to study the movement of cells and subcellular structures.

5. Automotive and aerospace industry, to measure the deformation of materials and components, and to monitor the performance of engines and other critical systems.

6. Optical testing, to measure the surface quality of optical components such as lenses and mirrors.

7. Nanotechnology, to measure the thickness of thin films and to characterize the properties of nanoscale materials.

4. Laser Triangulation

Laser triangulation is a technique used for non-contact measurement of distances, typically in industrial or scientific applications. It works by emitting a laser beam onto a surface and measuring the position of the reflected light with a detector.

4.1 Working Principle

The basic principle behind laser triangulation is the laser source, detector and a processor. The beam is directed towards a surface and reflected back to the detector in the shape of a "triangle".The position of the reflected light on the detector allows calculating the distance between the sensor and the surface as a result of clear difference.

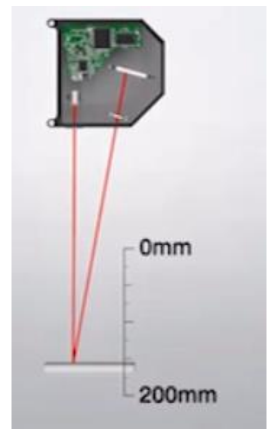


Figure 10 Laser Triangulation Sensor (Micro-Epsilon)

1. Emission; The laser beam is generated by a laser source and directed towards the surface being measured. Typically, the beam is focused on a small spot on the surface aiding accuracy.
2. Detection; The reflected light from the surface is captured by a detector, a photodiode or a CCD sensor. The position of the reflected light onto the detector is

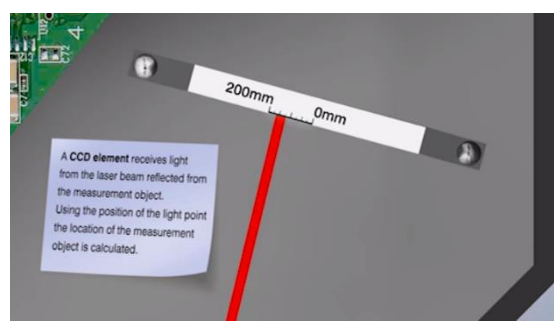


Figure 11 CCD inside a Laser Triangulation sensor (Micro-Epsilon)

used to calculate the distance between the sensor and the surface.

3. Processing; This is achieved through know properties of the laser wavelength, angle of incidence.

Eddy current sensors and CCD sensors are all non-contact measurement techniques used to measure physical properties of objects. While they have some similarities in their application, there are also some differences in their operation.

Eddy current sensors uses the principle of eddy current formation to sense displacement, it creates high frequency magnetic fiels by flowing high frequency current to the coil inside the sensor head [20]. The distance between the sensor and the conductive material can be calculated based on the strength of the magnetic field and change in impedance as a function of distance. Eddy current sensors are often used in industrial applications such as metal processing, where they can measure the thickness of metal sheets or the position of a moving metal surface especially useful in many engine optimisations such as crankshaft axial movement and cylinder head breathing. [21]

CCD (charge-coupled device) sensors are electronic devices used to capture and process optical images. They work by converting light into electrical signals, which are then processed to form an image, made of a photoactive region and transmission region where light shining on the photoactive region accumulates an electrical charge in the transmission region of equivalent intensity. [22]

While all both of them allow us for non-contact measurements, they differ in their use and operation. Laser triangulation is primarily used for distance measurements, while eddy current sensors are used for measuring physical properties. In terms of their physical operation, laser triangulation relies on a laser beam being emitted and reflected back to a detector, while eddy current sensors rely on the induction of eddy currents in a conductive material which limits is range greatly as it need be right next the part its measuring and the material needs to magnetic as well. CCD sensors rely on the conversion of light into electrical signals to form an image. While there may be similarities in their operation they each have their own requirements with different operational principles.

4.2 Operational Requirements

1. Surface properties; The surface being measured needs to have a certain level of reflectivity for the laser beam to be effectively reflected back to the detector, either too high or too low would not be suitable. [23]

2. Distance range; Laser triangulation is most accurate within the specified distance range.

3. Angle of incidence; The angle at which the laser beam hits the surface can affect the accuracy of the measurement, setup of the sensor requires some accuracy.

4. Laser specifications; Properties of the laser such as wavelength and power affect the accuracy and resolution of measurement, the laser chosen must meet the requirements of the application.

5. Detector specifications; The type and quality of the detector used to capture the reflected light can also affect the accuracy and resolution of the measurement. Detectors with high sensitivity and low noise are ideal for laser triangulation measurements.

6. Environmental conditions; factors such as temperature, humidity, and vibration can affect the accuracy of the measurement, a stable environment is required.

7. Calibration; To ensure accurate measurements, laser triangulation systems need to be calibrated periodically. Calibration involves adjusting the system to a known distance and verifying that the measurement results match the expected value.

4.3 Range and Resolution

The range of laser triangulation varies depending on the sensor used or the application, for short-range applications such as thickness measurements a few millimetres to centimeters would suffice but for longer range applications such as 3d scanning the body for a car for example, sensors with greater ranges would be more appropriate. The range sometimes called span, is the working distance between the endpoints over which the snsor can reliably measure or the limits of the CCD. [23]

The resolution of a laser triangulation system can vary from a few microns to a few millimeters, depending on the specific application and the components used, factors towards resolution include sensitivity, the size of the spot and the distance to the object.

Typically, achieving higher resolution necessitates the use of more sensitive sensors, which can incur additional costs. The resolution of a laser triangulation system is additionally influenced by various factors, including noise, drift, and environmental conditions, all of which have the potential to diminish measurement accuracy. To attain both high resolution and accuracy, it is crucial to meticulously calibrate and design the system in a manner that mitigates the influence of these factors.

4.4 Applications

Quality control in manufacturing: Laser triangulation systems are to measure the thickness, height, and surface roughness of products in real-time during the manufacturing process directly on the production line, ensuring consistent quality and reducing waste. [23]

Robotics: systems in robotics for 3D object recognition, tracking, and grasping. This can be useful in various applications, such as assembly line automation and warehouse management.

Aerospace; measuring surface characteristics for defects.

Automotive: used for geometry profile checking on body parts or even preemptive suspension changes by placing sensors to detect the road surface.

Laser triangulation is very useful as it has fast results and can be used in many different applications since it can be setup and implemented relatively at ease when compared to other remote distance measurements.

5. Experimental Setup

5.1 Introduction

The aim of my experiment is to compare the thickness glass samples between a physical contact measurement from a micrometer screw gauge versus two non-contact methods, confocal chromatic measurement principle and laser triangulation.

I am also conducting an additional experiment with a linear actuator with PIShift Stick-Slip Piezo motor to compare the measurement difference in the two sensors at a scale practical to both. The step size is not defined and is rather expressed as a step velocity so it will be interesting to find the average step size. To achieve this I had driven the motor forwards and backwards 10 steps, firstly to determine the step size and secondly, to find if the motor would return back to its initial position.

5.2 Apparatus

For the analysis of remote distance measurements of non-contact nature, I had two available sensors, the first being the Confocal Chromatic Measurement sensor "confocalDT IFS2404/90-2" and the second for Laser triangulation "optoNCDT 1420". Both sensors manufactured by Micro-Epsilon.

5.2.1 ConfocalDT IFS2404/90-2

This sensor has the following base properties:

- Measuring range: 2 mm
- Linearity max: 1 µm

Figure 12 ConfocalDT IFS2404/90-2 (Micro-Epsilon)

- Resolution: 0.040 µm
- 90° lens for installation in restricted spaces
- Max tilt angle: ±12°

The start of the measuring range is at 9.6mm measured from the sensor axis, which means anything in between is not suitable for a measurement and samples to for distance measurements must be placed after this range and before 11.6mm from the sensor axis to provide and reading. When measuring one-sided thickness however logically the sample must be under 2mm in thickness as we will observe later. There is also the max tilt angle to consider which is ±12° where nearing the limit values reduces the accuracy and it is based on the usable signal on reflecting surfaces.

The confocal sensors require a controller called a Light-intensive controller with high measurement speed. The controllers themselves support upto 30khz but the value will be limited to the sensor predetermined capabilities.

5.2.2 OptoNCDT 1420

This sensor has the follwing base properties:

- Measuring ranges (mm) 10
- Linearity from 8µm
- Repeatability from 0.5µm
- Measuring rate 4kHz

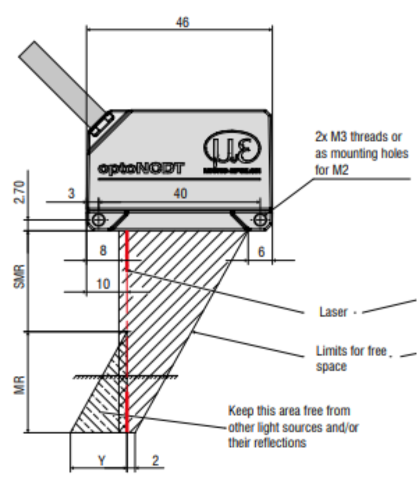


Figure 13 OptoNCDT 1420 (Micro-Epsilon)

Like most of the sensors in their class they have a SMR which is its start of measuring range, which for this sensor is 20mm from the last physical component of the sensor where the same rules as before apply. With the measuring range of 10mm there is much more distance to be worked with especially in thickness measurements.

5.2.3 Piezo Motor

The used motor is a N-422 Linear Actuator with Piezo Motor, which does not have a step size as I mentioned earlier but defined by a velocity of over 5mm/s.

Figure 14 N-422 Linear Actuator with Piezo Motor (PI)

Figure 15 E-870 PIShift Drive (PI)

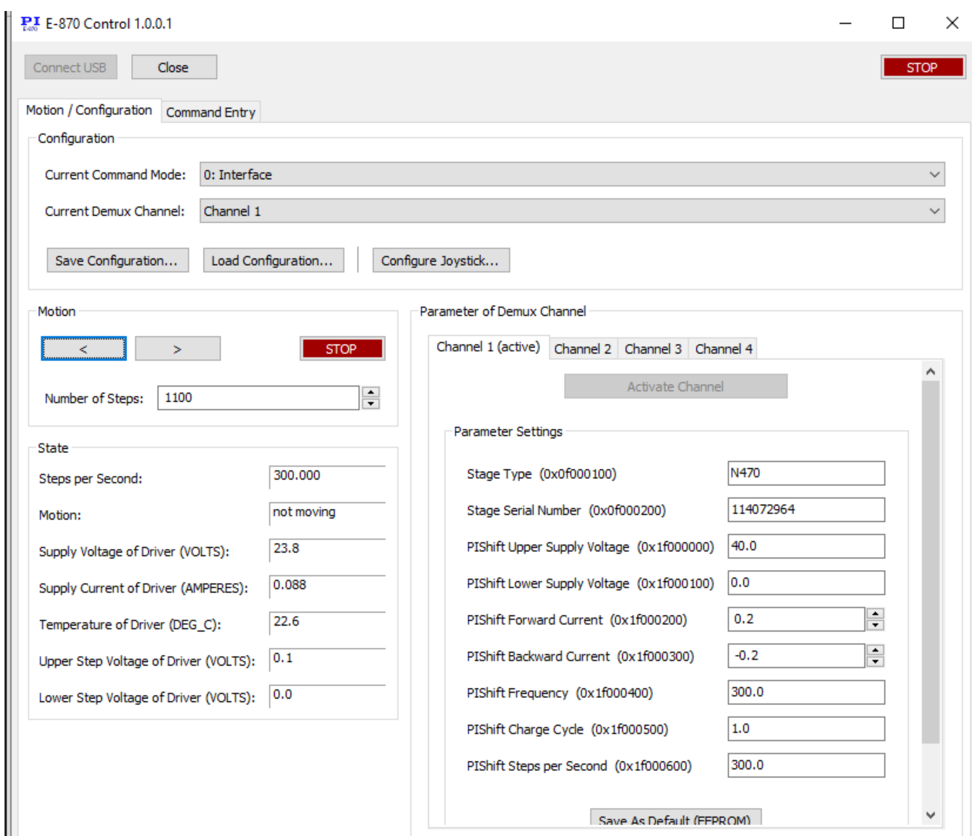


Figure 16 PIShift Drive Controller

The PIShift drive figure 16 is controlled by the program in figure 14, where you can enter a custom number of steps it would translate.

5.2.4 Measurement Samples

5 samples of Bk7 glass of various dimensions were used and their respective thicknesses measured by a micrometer screw gauge(Daqua, ±0.001mm. 0-25mm) are presented in the table below.

Table 1 Contact Measurement of Glass Thickness

Glass	1	2	3 (lens)	4	5
Thickness [±0.01mm]	1.15	0.15	3.08	3.98	3.61

5.2.5 Sensor Mounts

We cannot just hold the sensor above the target with a clamp for the glass thickness measurements as they need to be compared to each other therefore with the use of Autodesk Fusion 360 I had designed a few fixtures to hold the probe at a fixed distance from the glass samples. The reason as to why I used this software is just due to my familiarity with Fusion 360 and its relative ease of use compared to other software packages in the market.

I designed a few custom mounts to place the glass in the measuring range as well as perpendicular to the sensor axis. This also allows the measurement consistency as the sensor position is unchanged during the analysis which emulates a functional environment that is used in the industry where the sample would move under a stationary sensor.

For the Piezo Motor experimental setup, it was unnecessary to create a mount. Instead, the sensors were mounted by a clamp at a distance within the measuring range as I will show in figure 35 and 36.

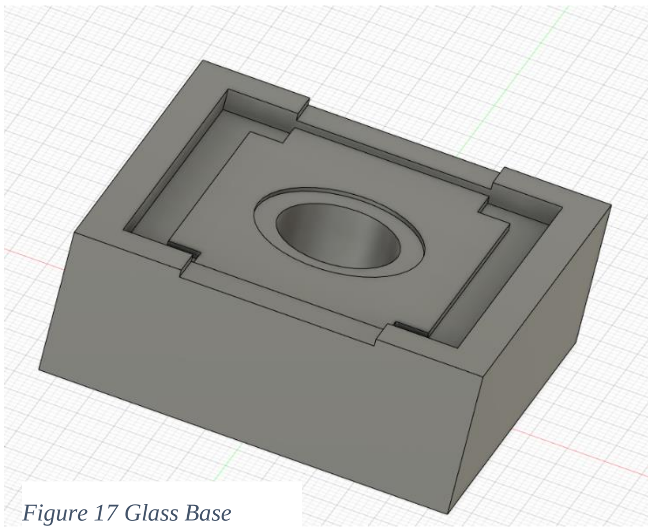


Figure 17 Glass Base

Initially without much testing or experience with the sensors I had wanted a common base for both sensors where each glass sample had a recess to which their center on the sensor axis is all at the same point. The sensor would have been calibrated to a midpoint on the above base with the use of a 3d printed pillars to place the sensor at a distance above the base with use of a clamp stand available at the lab. This design obviously did not work mainly since tilt angle would be completely based on my visual of it and result not being easily repeatable as the sensor as to be placed in the same way each time, to this problem the next iterations were focused towards being a stand or a mount.

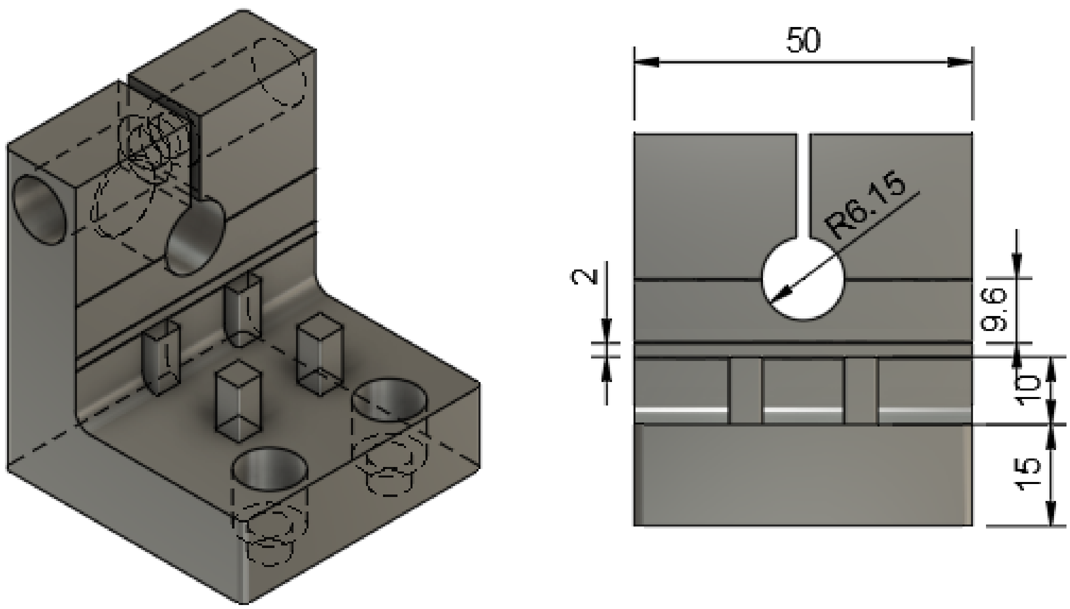


Figure 18 Confocal Sensor Mount

The figure 15 represents the mount for the Confocal Sensor, the recessed lines in the front view are features to indicate the measuring range. The top line is the start of the measuring range up until the middle line afterwhich there is a 2mm gap to the next line that is the proper measuring range. The 4 pillars in the middle are to elevate the samples of glass from the base to provide better placement under the sensor where the sensor spot would be in the middle of the sample at all times.

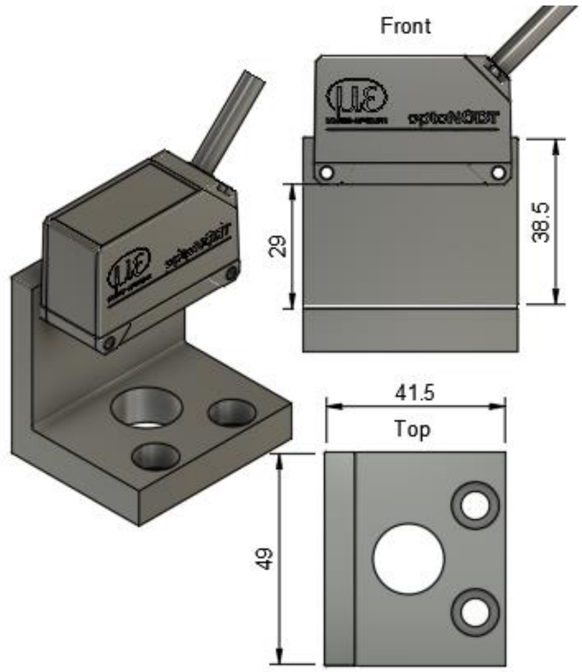


Figure 16 Laser Triangulation Sensor Mount

The above figure is the designed Laser Triangulation Mount, unlike the previous confocal model fiducial markers are not present, this is because the base is at 1mm from the end of the measuring range being 30mm and knowing my glass samples are all under 10mm it was not necessary. The use of an elevated stand is also not necessary since the laser comes offset from the middle of sensor and the zero-ing function of the sensor required a surface to calibrate to.

6. Glass Thickness Measurement

6.1.1 Confocal Sensor Setup

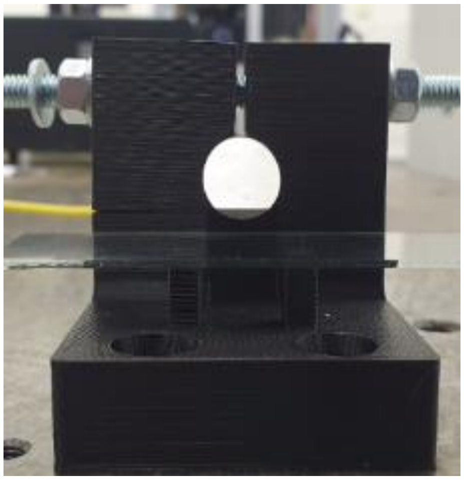


Figure 20 Confocal Glass Setup Front View

Figure 19 Confocal Glass Setup Top View

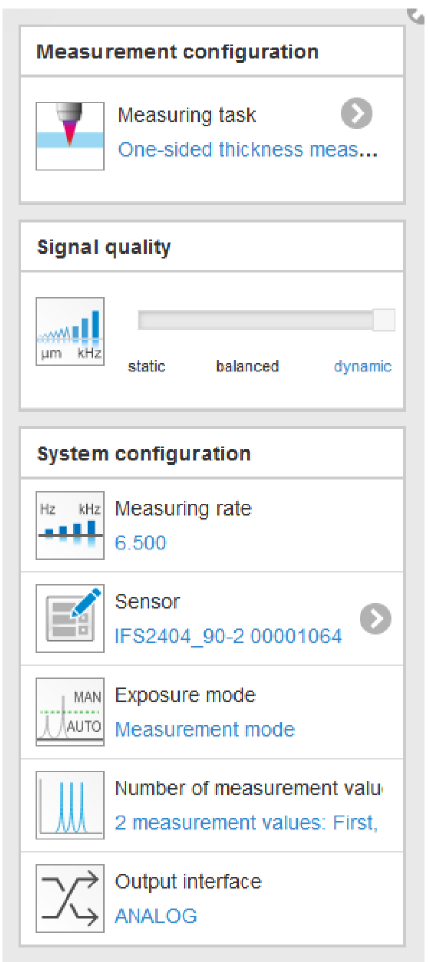
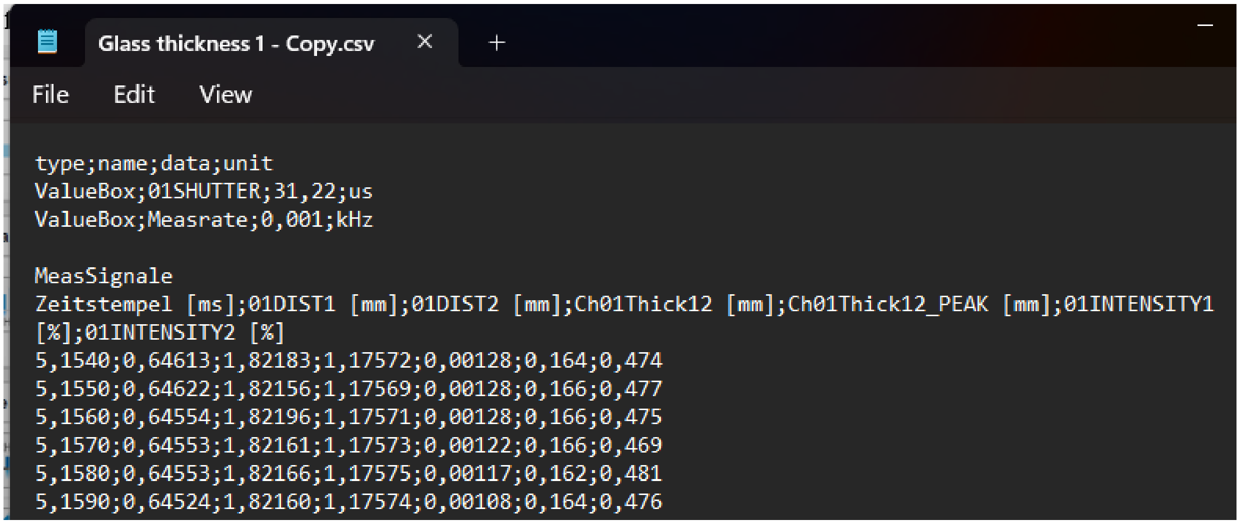


Figure 21 Confocal Glass Software Settings

The figures, 19 and 18, above are the physical setup of the Confocal Sensor. The figure 20 to the left presents the settings used in the software where the primary setting being a one-sided thickness measurement. Enabling this setting in the software automatically outputs the thickness it measures by the means of peaks and their respective intensities, the program can then automatically output the thickness value onto a graph which for my purposes I had used the raw data from a .csv file as the figure 21.



Glass thickness 1 - Copy.csv

File Edit View

```
type;name;data;unit
ValueBox;01SHUTTER;31,22;us
ValueBox;Measrate;0,001;kHz

MeasSignale
Zeitstempel [ms];01DIST1 [mm];01DIST2 [mm];Ch01Thick12 [mm];Ch01Thick12_PEAK [mm];01INTENSITY1
[%];01INTENSITY2 [%]
5,1540;0,64613;1,82183;1,17572;0,00128;0,164;0,474
5,1550;0,64622;1,82156;1,17569;0,00128;0,166;0,477
5,1560;0,64554;1,82196;1,17571;0,00128;0,166;0,475
5,1570;0,64553;1,82161;1,17573;0,00122;0,166;0,469
5,1580;0,64553;1,82166;1,17575;0,00117;0,162;0,481
5,1590;0,64524;1,82160;1,17574;0,00108;0,164;0,476
```

Figure 22 Output data .csv

It is not necessary for my use that I need the intensity of the peaks, but after a few attempts especially in the laser triangulation sensor we can spot anomolies with relative ease in the output file. With the output.csv file I had uploaded it into Microsoft Excel and processed the results into comprehensible graphs.

When discussing implementation into custom tailor made programs for the industry it would be much easier to directly take the output from the program provided by Micro-Epsilon (figure 18) as it would automatically give you the thickness in realtime where a filter can be setup to automate sample thickness tests or quality control.

6.1.2 Results

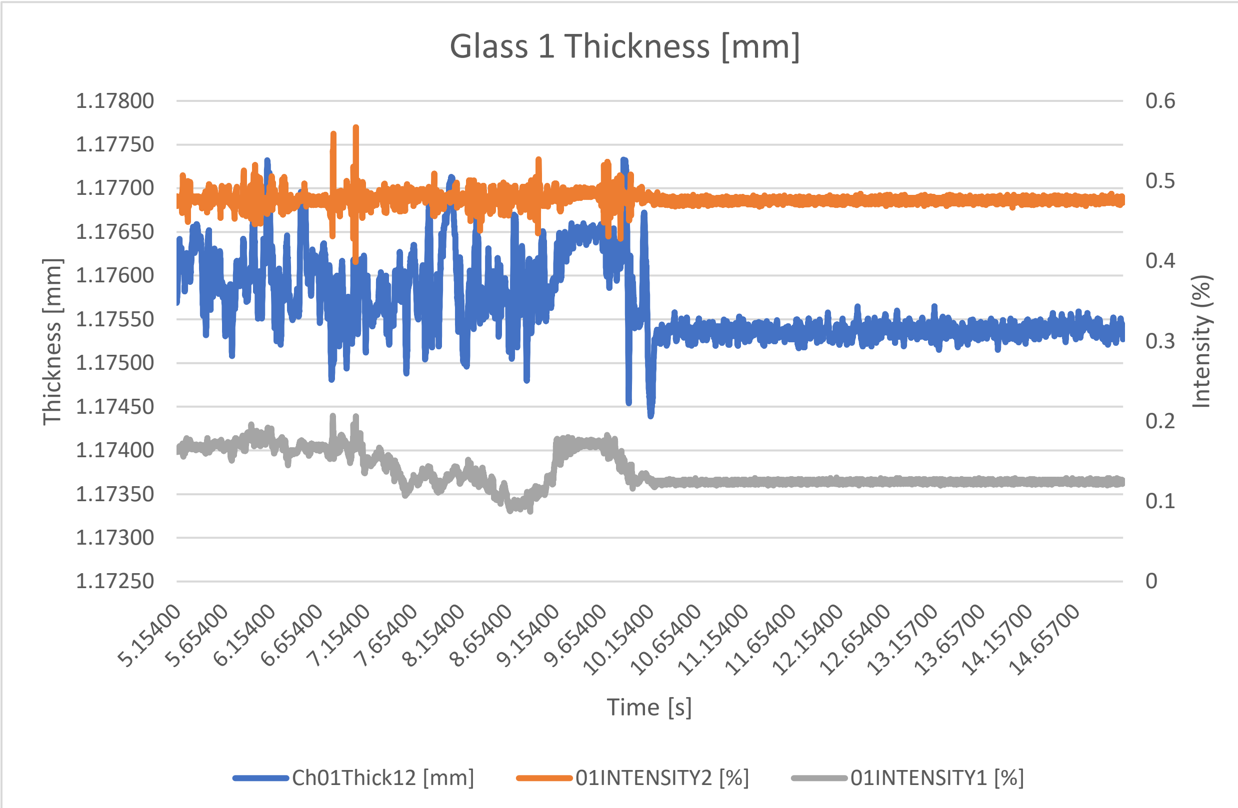


Figure 23 Thickness and Intensity of Glass 1

Mean	Mode	Median	Range
1.175666	1.17541	1.17546	-0.00294

Table 2 Glass 1 Measurement Statistics

	A	B	C	D	E	F	G
1	Column1	Column2	Column3	Column4	Column5	Column6	Column7
2	type	name	data	unit			
3	ValueBox	01SHUTTER	31.22	us			
4	ValueBox	Measrate	0.001	kHz			
5							
6	MeasSignale						
7	Zeitstempel [ms]	01DIST1 [mm]	01DIST2 [mm]	Ch01Thick12 [mm]	Ch01Thick12_PEAK [mm]	01INTENSITY1 [%]	01INTENSITY2 [%]
8	5.154	0.64613	1.82183	1.17572	0.00128	0.164	0.474
9	5.155	0.64622	1.82156	1.17569	0.00128	0.166	0.477
10	5.156	0.64554	1.82196	1.17571	0.00128	0.166	0.475
11	5.157	0.64553	1.82161	1.17573	0.00122	0.166	0.469
12	5.158	0.64553	1.82166	1.17575	0.00117	0.162	0.481
13	5.159	0.64524	1.8216	1.17574	0.00108	0.164	0.476
14	5.16	0.64523	1.82165	1.17576	0.00107	0.164	0.472
15	5.161	0.64524	1.82143	1.17576	0.00105	0.165	0.477
16	5.162	0.6452	1.82147	1.17578	0.00105	0.165	0.474
17	5.163	0.64541	1.8214	1.17581	0.00105	0.166	0.474
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figure 24 Excel Processing of Data

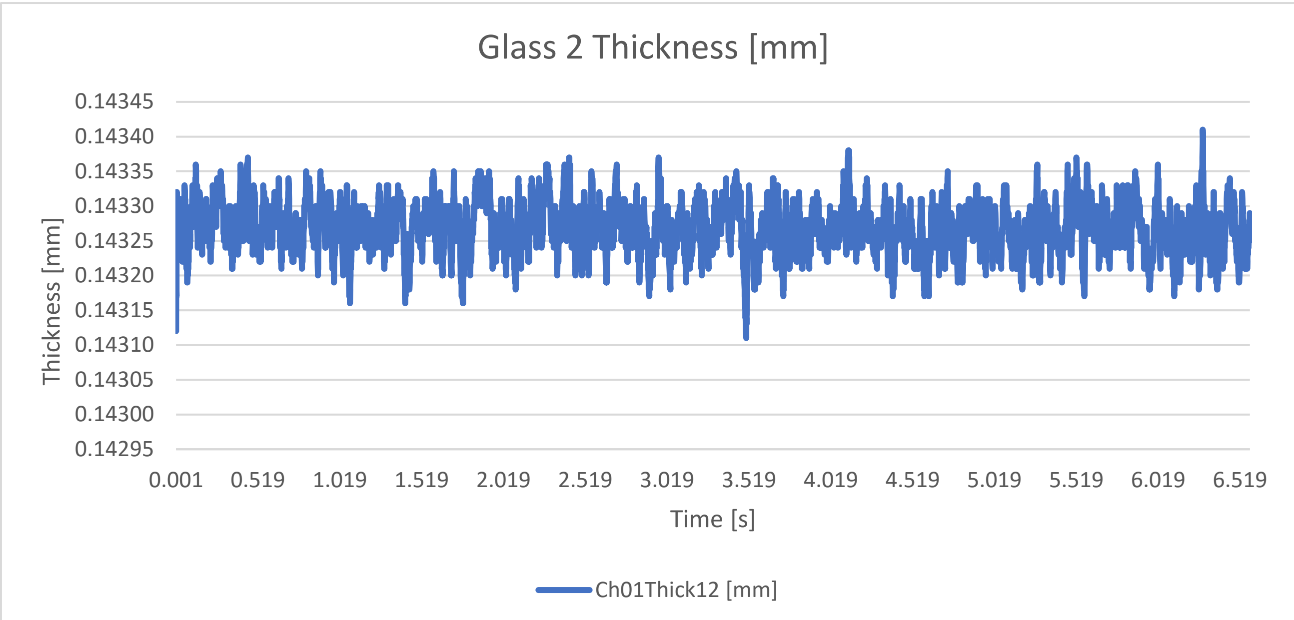


Figure 22 Thickness Plot of Glass 2

Mean	Mode	Median	Range
0.143269	0.14327	0.14327	-0.0003

Table 3 Glass 2 Measurement Statistics

6.2.1 Laser Triangulation Sensor Setup

Figure 26 Laser Triangulation Glass Setup Top view

Figure 25 Laser Triangulation front view

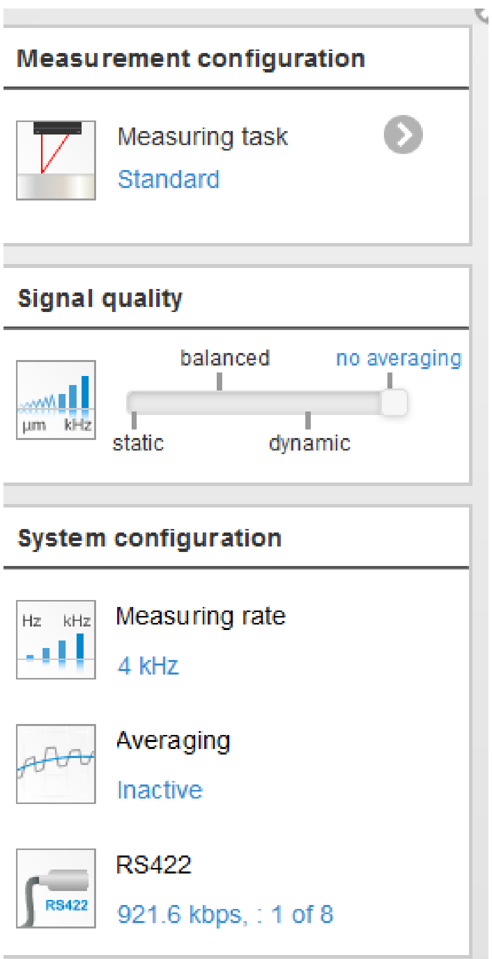
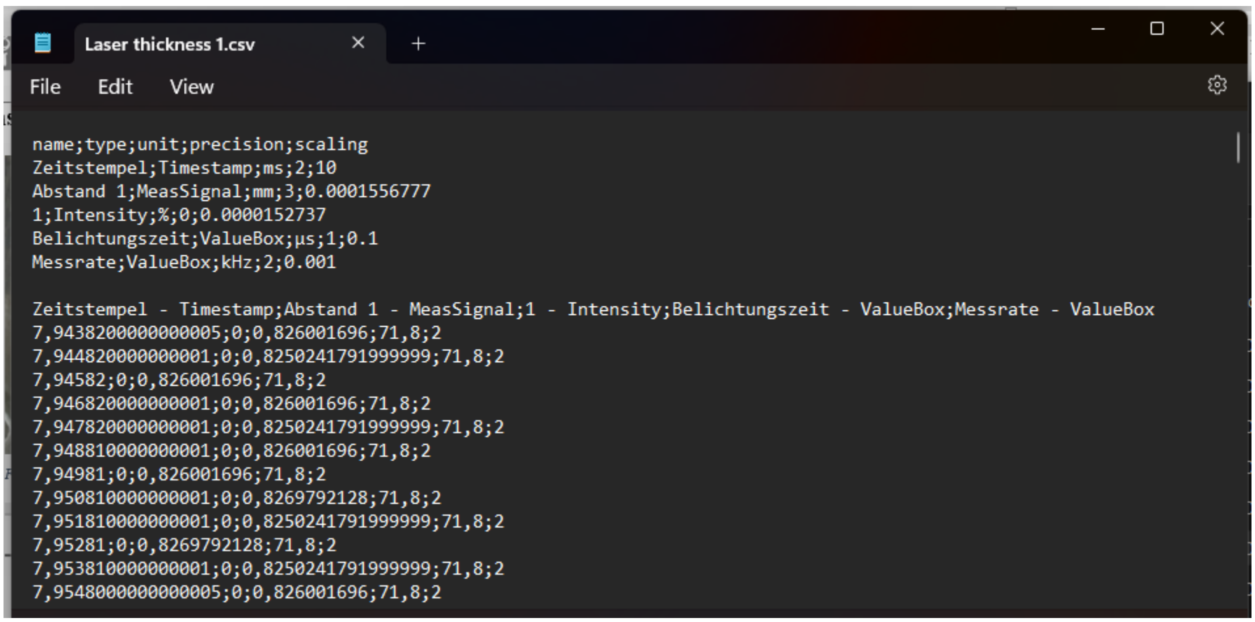


Figure 27 Laser Triangulation

Figure 25 and 24 are the physical setup of the laser triangulation sensor. The settings shown in figure 26 are slightly different from that of the confocal sensor since the measuerment methods are very different. Compared to the confocal sensor the laser there is not the same method of obtaining the thickness value but the laser triganulation sensor has its own method known as Zeroing/Mastering where the flat base of the 3d print comes into play. The Zeroing allows me to set the start of the measuring range and therefore the thickness can be found from the by the first peak, this is important since the there are multiple peaks and where the zero is the base of the stand the first peak is the surface of the glass. In the settings you must configure the sensor to output the value of the first peak for the results I needed. Since the base of my stand is the zeroed value you will notice that the values obtained are in the negative as the glass is above the zero point but still in the measureing range.



Laser thickness 1.csv

File Edit View

```
name;type;unit;precision;scaling
Zeitstempel;Timestamp;ms;2;10
Abstand 1;MeasSignal;mm;3;0.0001556777
1;Intensity;%;0;0.0000152737
Belichtungszeit;ValueBox;µs;1;0.1
Messrate;ValueBox;kHz;2;0.001

Zeitstempel - Timestamp;Abstand 1 - MeasSignal;1 - Intensity;Belichtungszeit - ValueBox;Messrate - ValueBox
7,9438200000000005;0;0,826001696;71,8;2
7,944820000000001;0;0,8250241791999999;71,8;2
7,94582;0;0,826001696;71,8;2
7,946820000000001;0;0,826001696;71,8;2
7,947820000000001;0;0,8250241791999999;71,8;2
7,948810000000001;0;0,826001696;71,8;2
7,94981;0;0,826001696;71,8;2
7,950810000000001;0;0,8269792128;71,8;2
7,951810000000001;0;0,8250241791999999;71,8;2
7,95281;0;0,8269792128;71,8;2
7,953810000000001;0;0,8250241791999999;71,8;2
7,9548000000000005;0;0,826001696;71,8;2
```

Figure 28 Laser Triangulation Output .csv

The laser triangulation output file is a bit messier than the confocal one but can still be processed in excel with more modifications.

6.2.2 Results

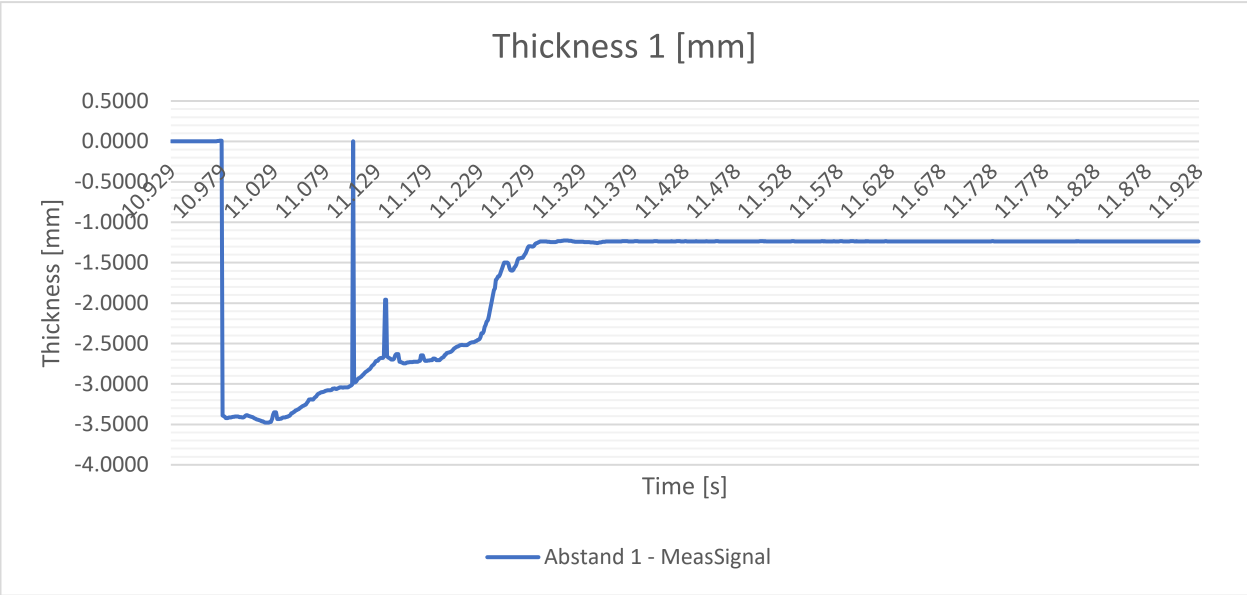


Figure 29 LT Thickness Plot of Glass 1

Mean	Mode	Median	Range
-1.70715	-1.236	-1.23800	-3.48700

Table 4 LT Thickness Statistics of Glass 1

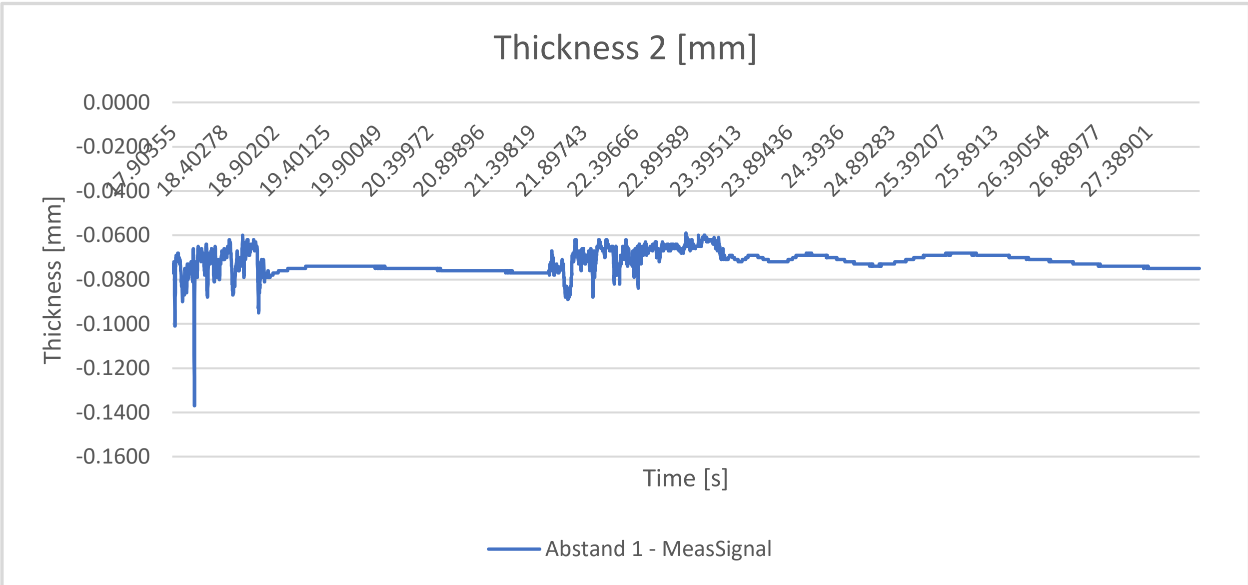


Figure 30 LT Thickness Plot of Glass 2

Mean	Mode	Median	Range
-0.07220	-0.074	-0.073	-0.078

Table 5 LT Thickness Statistics of Glass 2

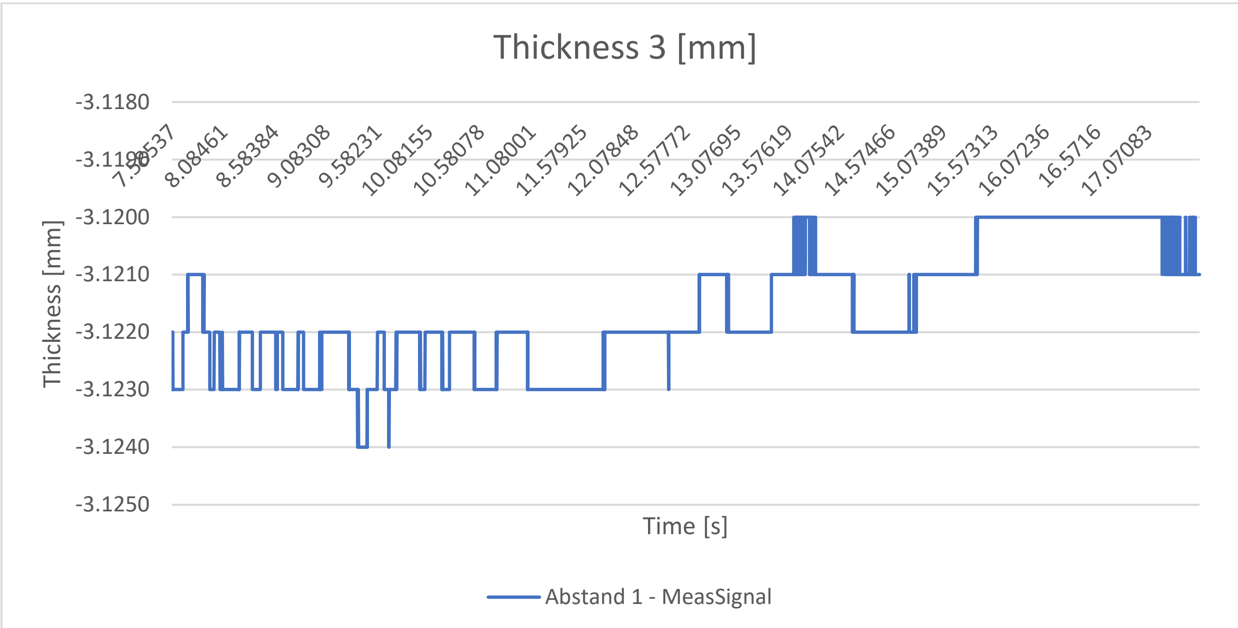


Figure 31 LT Thickness Plot of Glass 3

Mean	Mode	Median	Range
-3.12163	-3.122	-3.122	-0.004

Table 6 LT Thickness Statistics of Glass 3

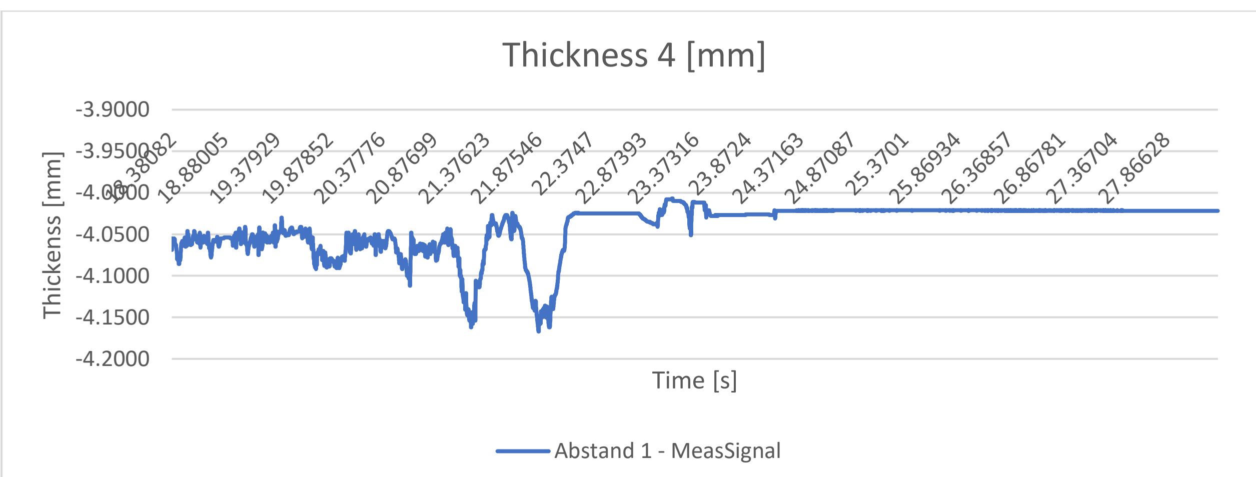


Figure 32 LT Thickness Plot of Glass 4

Mean	Mode	Median	Range
-4.04030	-4.021	-4.025	-0.16

Table 7 LT Thickness Statistics of Glass 4

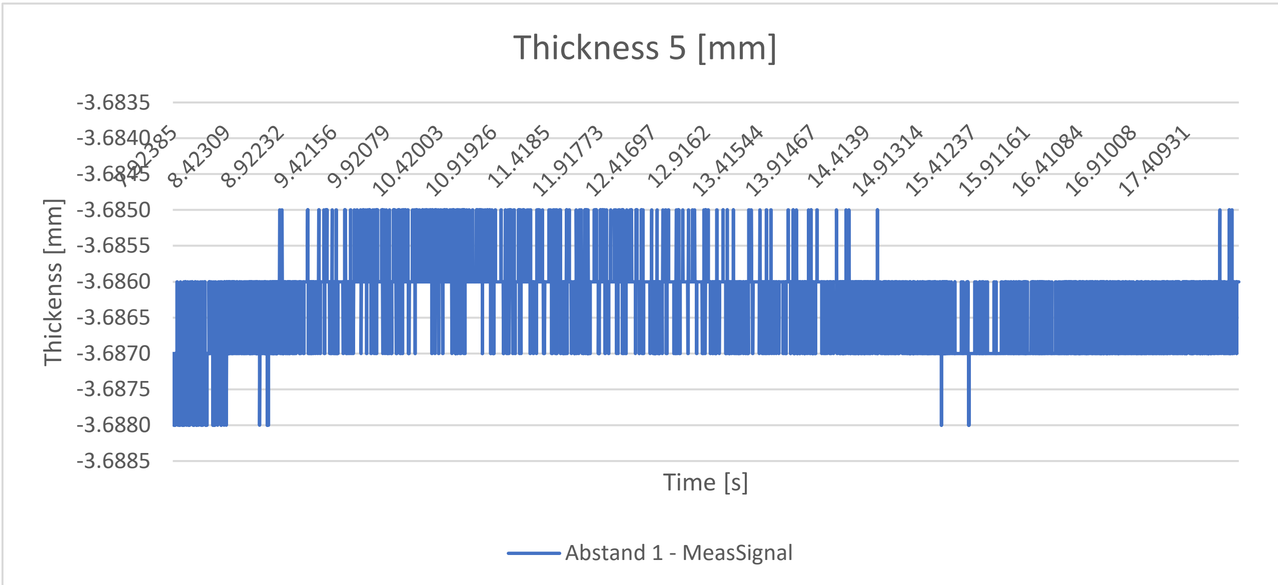


Figure 33 LT Thickness Plot of Glass 5

Mean	Mode	Median	Range
-3.68631	-3.686	-3.686	-0.003

Table 8 LT Thickness Statistics of Glass 5

	A	B	C	D	E
1	Column1	Column2	Column3	Column4	Column5
2	name	type	unit	precision	scaling
3	Zeitstempel	Timestamp	ms	2	10
4	Abstand 1	MeasSignal	mm	3	0.0001556777
5	1	Intensity	%	0	0.0000152737
6	Belichtungszeit	ValueBox	µs	1	0.1
7	Messrate	ValueBox	kHz	2	0.001
8					
9	Zeitstempel - Timestamp	Abstand 1 - MeasSignal	1 - Intensity	Belichtungszeit - ValueBox	Messrate - ValueBox
10	7.58537	-3.122	0.832844314	71.7	2
11	7.58637	-3.122	0.831866797	71.7	2
12	7.58737	-3.122	0.832844314	71.7	2
13	7.58837	-3.122	0.83382183	71.7	2
14	7.58937	-3.122	0.832844314	71.7	2
15	7.59036	-3.122	0.834799347	71.7	2
16	7.59136	-3.123	0.832844314	71.7	2
17	7.59236	-3.122	0.83382183	71.7	2
18	7.59336	-3.122	0.832844314	71.7	2

Figure 34 Excel Processing of Laser Triangulation Data

6.3Summary

Glass Sample	Measurement Method [mm]				
	Micrometer [±0.01mm]	Confocal [±0.00001mm]	Con. Deviation [±0.00001mm]	Laser [±0.001mm]	Las, Deviation [±0.001mm]
1	1.15	1.175666	0.025666	1.70715	0.56
2	0.15	0.143269	-0.006731	0.07220	-0.08
3	3.08			3.12163	0.04
4	3.98			4.04030	0.06
5	3.61			3.68631	0.07

Table 9 Glass Thickness Summary

Abstand 1-MeasSignal, in the legends of the laser triangulation graphs represent the thickness signal from the extracted file. The fluctuations in the graphs are from moving the glass samples to obtain thickness values from all around the glass samples, they may look like different graphed series but it is dependent on the axis range or rather the range of results in a measurement.

At first view we can see that I did not achieve perfect results as my aim was to match the sensors readings to the micrometer screw gauge. To start with confocal sensor which gave me the closest results, I would regard the error to be associated with measurement location with the glass. With the micrometer where I measured multiple points to attain a mean value, I cannot be sure if I measured the very same points under the confocal sensor.

7. Piezo Measurement

7.1 Setup

Figure 36 Confocal on Piezo Motor Setup

Figure 35 Laser Triangulation with Piezo Motor Setup

As the two sensors are mounted onto a clamp stand and then calibrated using the system software by Micro-Epsilon to make sure they were in range and reading properly. With the triangulation sensor it is easy to check the position without connecting to a computer since it has led indicators for when it is in range. The confocal sensor on the other hand needs some more time with the setup especially using a clamp, the software must be running in tandem for this setup.

7.2 Results

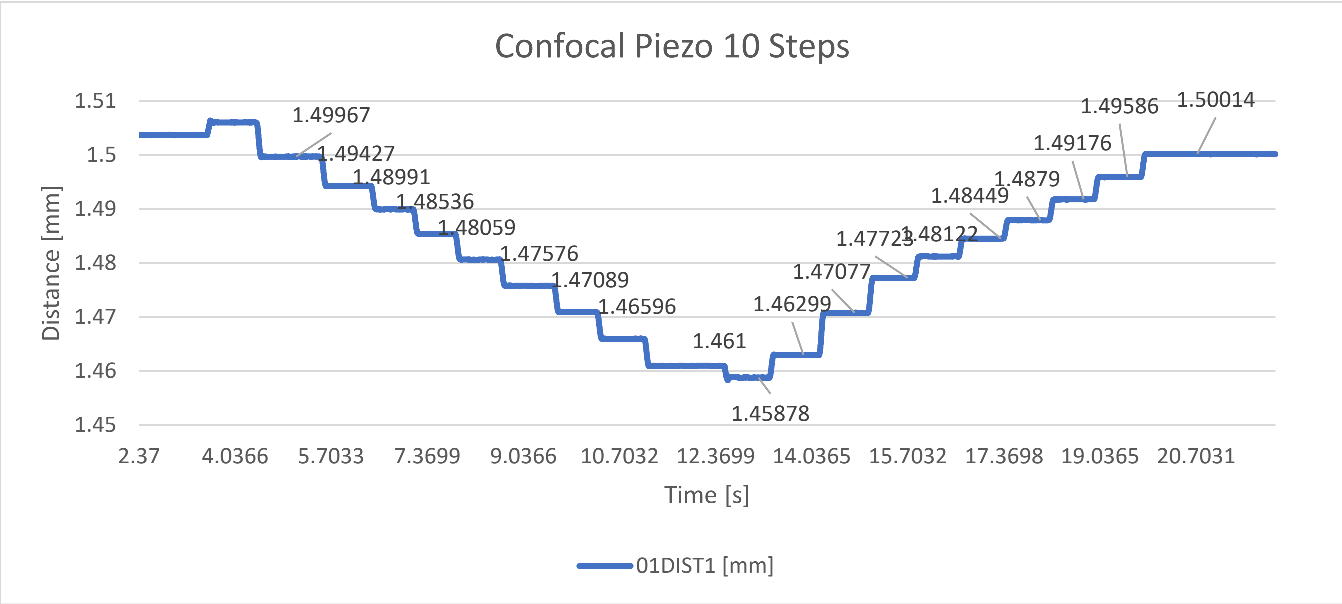


Figure 37 Confocal Sensor Piezo Measurement

Step	1	1'	2	2'	3	3'	4	4'	5
Distance [±0.00001 mm]	1.49967	1.50014	1.49427	1.49586	1.48991	1.49176	1.48536	1.4879	1.48059
Difference [±0.00002 mm]			-0.00540		-0.00436		-0.00455		-0.00477
Difference ' [±0.00002 mm]				-0.00428		-0.00410		-0.00386	

5'	6	6'	7	7'	8	8'	9	9'	10	Average
1.48449	1.47576	1.48122	1.47089	1.47723	1.46596	1.47077	1.461	1.46299	1.45878	
	-0.00483		-0.00487		-0.00493		-0.00496		-0.00222	-0.00454
-0.00341		-0.00327		-0.00399		-0.00646		-0.00778	-0.00421	-0.0046

Table 10 Confocal Sensor Piezo Measurement

The table above is one table seperated into two to fit the space on this page. On the graph the data labels are the points I had taken into account. The step number denotes the movement of the motor, forwards is the normal step and the prime value represents the respective backward step. Where ideally 1 would be at the same location as 1’.

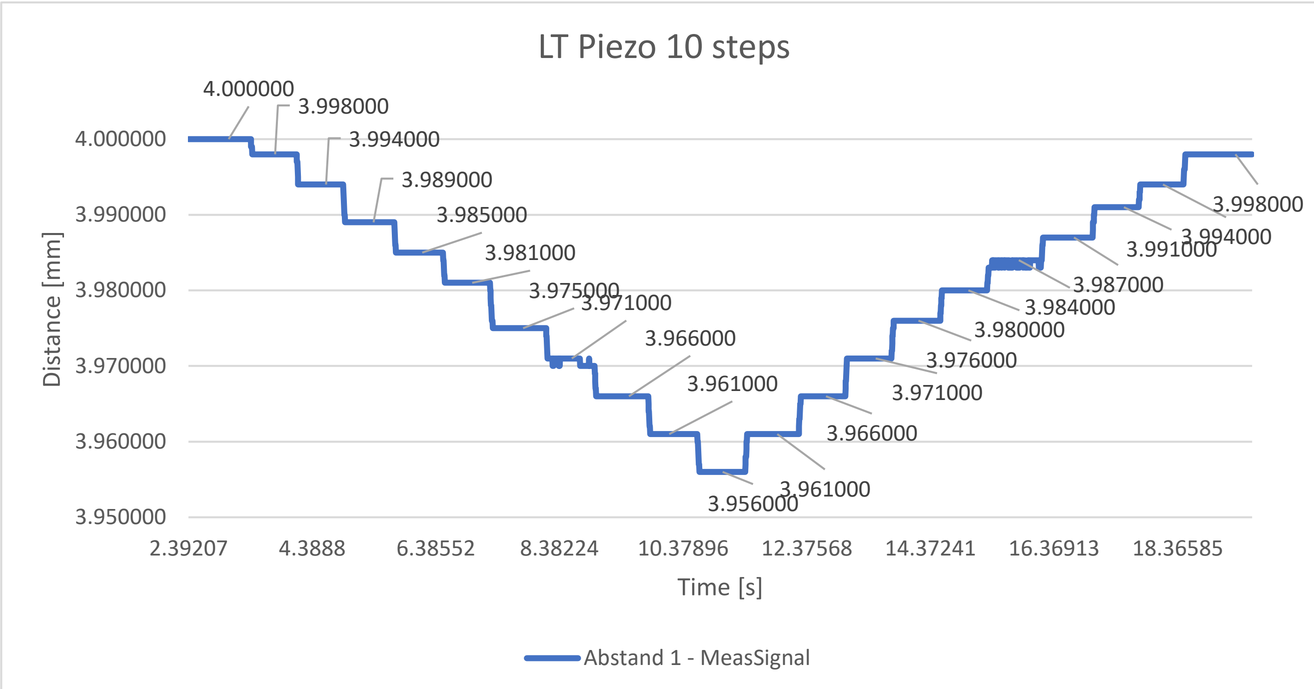


Figure 38 Laser Triangulation Sensor Piezo Measurement

Step	1	1'	2	2'	3	3'	4	4'	5	5'
Distance [±0.001 mm]	4.000	3.998	3.998	3.994	3.994	3.991	3.989	3.987	3.985	3.984
Difference [±0.002 mm]			-0.002		-0.004		-0.005		-0.004	
Difference' [±0.002 mm]				-0.004		-0.003		-0.004		-0.003

Step	6	6'	7	7'	8	8'	9	9'	10	10'	11	Average
Distance [±0.001 mm]	3.981	3.981	3.975	3.976	3.971	3.971	3.966	3.966	3.961	3.961	3.956	
Difference [±0.002 mm]	-0.004		-0.006		-0.004		-0.005		-0.005		-0.005	-0.0044
Difference' [±0.002 mm]		-0.003		-0.005		-0.005		-0.005		-0.005	-0.005	-0.0042

Table 11 Laser Triangulation Sensor Piezo Measurement

To be able to process the data.csv file externally you must lower the frequency of the sensor since a higher frequency would increasing the amount of outputs which has a limit in the sensor software.

7.3 Summary

With this experiement I had made perpendicular checks to make sure I can achieve accurate results.

Mean Step Displacement for 10 steps [µm]		Displacement of 1 step [µm]
Confocal [±0.02µm]	4.54	0.454
Confocal' [±0.02µm]	4.60	0.460
Laser [±2 µm]	4.40	0.440
Laser' [±2 µm]	4.42	0.420

Table 12 Step Displacement of Sensors on Piezo Motor

We can observe from the tables that the laser triangulation had on average a better result but I can also argue that is also due to the resolution of the confocal sensor being much greater. With the higher resolution the confocal sensor has an far lower uncertainty and the values have a difference of ‘0.06 µm’ between the 1 step displacement calculations.

For the piezo experiment I processed the data in the same way as before in Microsoft Excel as I received the same data formats as I presented in the figure 24 and 34.

8. Conclusions

My main comment for the on the glass thickness would be that the only controlled sample of glass with even thickness all around is Glass 2, this created a number of variations in the laser triangulation thicker glass pieces where if I were to reattempt that it would be with more manufactured and known thickness samples.

It is important to remember with both sensors datasheets it is stated that for thickness measurements to be done at the middle of the measuring range or at least near it. For the confocal sensor this was not a problem and therefore I would like to attribute its accuracy to this. The laser triangulation sensor mount of mine creates the end of measuring range at near 9mm of its 10mm.The laser triangulation mount I have positioned to allow a measuring range of 1-9mm, a redesign would be where the physical end of measuring range at the base of the 3d print is nearer to the middle of the sensor's measuring range which would provide better results. A clear real-world advantage of the laser triangulation method over the confocal sensor in the experiment is the zeroing ability, when implemented into a manufacturing process it doesn't matter if the material is transparent since it will give difference from the zero-ed base to the surface of any material. Then there is also the ability to attain the thickness automatically for different materials from the confocal sensor which is very useful as well.

The sensor mounts 3d printed should in retrospect be checked at all angles for any warping which would drastically change my results obtained. Another possibility would be to a machined bed or even a 3d printed holder for gauge blocks, which if available is cost effective. A crucial takeaway being that the surface onto which the material is placed for measuring in my experiments or in an manufacturing process must be highly precise. The easier method to overcoming this would be a software solution where anyhow for thickness measurements we know that we should be close to the middle of the measuring range so then we may implement a software that takes into account the bed height before and after the sample as well as the average height of the sample, this would overcome a few unnecessary variations.

Where this thesis began with a brief outlook on remote distance measurement techniques and their characteristics in technical realization, range and resolution, I wanted this experiment to highlight the importance of sensor selection. Overall, I conclude that the use where in general purposes the laser triangulation sensor is very capable especially with its greater choice in range while for more refined and miniscule operations the confocal sensor is very helpful.

9. References

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